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16. ABSTRACT

Thirty-eight indices and measurements of trophic state were compared to evaluate their relative abilities to trophically rank a test set of 44 eastern and southeastern U.S. lakes, representing 17 states. Lake rankings based upon total phosphorus and chlorophyll a levels served as standards for evaluation of the indices by Spearman Rank Correlation procedures. Included among the indices and measurements tested are: ten new phytoplankton community-based indices developed at EPA's EMSL-Las Vegas; Vollenweider's, Dillon's, and Larsen and Mercier's loading models for estimation of lake ambient phosphorus; multivariate indices including Boland's PCl_1 and PCl_2 and the CERL TSI; single parameter indicators including Secchi disk transparency, total Kjeldahl nitrogen, total phosphorus, chlorophyll a, conductivity, algal assay control yield and phytoplankton concentration; and algal community-descriptive indices including Palmer's Organic Pollution Indices, Nygaard's Indices, number of phytoplankton species, Shannon-Wiener's Diversity Index, and Pielou's Evenness Component of Diversity; transformed single parameter indices by Carlson; and N/P ratio.

The new phytoplankton community-based indices turned in 4 of the top 5 performances against the chlorophyll a standard, while Secchi disk transparency, phosphorus loading models, multivariate analyses, and total Kjeldahl nitrogen provided strong rank correlations with total phosphorus.

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FOREWORD

Protection of the environment requires effective regulatory actions that are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach that transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report compares and evaluates the relative abilities of 38 indices and measurements of trophic state to rank a test set of 44 eastern and southeastern U.S. lakes, representing 17 states. Results of the comparisons will aid researchers, monitors, and watershed managers in the selection of the proper trophic index to meet their specific requirements. This report was written for use by Federal, State, and local governmental agencies concerned with water quality analysis, monitoring, and/or regulation. Private industry and individuals similarly involved with the biological aspects of water quality will find the document useful. For further information contact the Water and Land Quality Branch, Monitoring Operations Division.

George B. Morgan
Director
Environmental Monitoring and Support Laboratory
Las Vegas

SUMMARY

The purpose of this report is to describe several new phytoplankton community-based indices to lake trophic state and rate their performance against indices and measurements already in use. Indices and measurements of trophic state are highly desirable to aid states in meeting lake classification requirements under Section 305b and monitoring the success of Clean Lakes restoration efforts under Section 314 of the Water Bill (PL92-500). The large variety of indices and measurements which are available makes it difficult for users to choose the best one for specific lake monitoring or classification applications. A selection aid was developed using rank correlation procedures to rate the relative ability of each index or measurement to rank a test set of 44 lakes according to two trophic standards, mean summer total phosphorus and chlorophyll *a*.

Included among the indices and measurements tested are ten new community-based phytoplankton indices developed at EPA's EMSL-Las Vegas; Vollenweider's, Dillon's, and Larsen and Mercier's loading models for estimation of lake ambient phosphorus; multivariate indices including Boland's PCI_1 and PCI_2 and the CERL TSI; single parameter measurements including Secchi disk transparency, total Kjeldahl nitrogen, total phosphorus, chlorophyll *a*, conductivity; algal community-descriptive indices including Palmer's Organic Pollution Indices, Nygaard's Indices, Number of phytoplankton species, Shannon-Wiener's Diversity Index, and Pielou's Evenness Component of Diversity; transformed single parameter indices by Carlson; and N/P ratio.

The new phytoplankton indices were developed as a direct result of an extensive investigation of phytoplankton relationships to environmental conditions in 250 lakes from 17 eastern and southeastern States. Although several of these indices performed relatively well, all should be considered preliminary in nature, as refinements and more extensive testing are in progress.

Phosphorus is generally considered to be the most important nutrient associated with eutrophication of fresh waters, while chlorophyll *a* is considered the primary parameter for measuring the manifestations of nutrient enrichment, but results from calculation of the various indices and measurements tested showed important differences relative to the two standards. With the exception of total Kjeldahl nitrogen, which had agreement with both standards, indices and measurements that correlated well with the phosphorus standard showed poor rank correlation with the chlorophyll *a* standard. The converse was also true, those that correlated well with chlorophyll *a* did poorly with total phosphorus.

Phosphorus loading models were quite successful in ranking lakes relative to the phosphorus standard rankings but were unsuccessful when compared to the chlorophyll a rankings, i.e., they did not predict the primary manifestation of eutrophication. Secchi disk measurements closely approximated the rank orders of the loading models. High mineral turbidity, which binds phosphorus in a form unavailable to the algae and reduces the light reaching them, constitutes the primary reason for the poor correlation of loading models and Secchi measurements with the chlorophyll a standard.

Such widely-used biological indices as Palmer's Organic Pollution Index, Nygaard's Trophic State Indices, Shannon-Wiener's Phytoplankton Diversity Index, and Pielou's Evenness Component of Phytoplankton Diversity were generally ineffective for lake trophic state assessment. However, several phytoplankton community-based trophic indices introduced in this study were shown to be more effective in trophically ranking lakes, relative to the chlorophyll a standard, than most of the widely used trophic indices or measurements tested. The strong performance of phytoplankton community-based indices suggests that the basic approach is sound and that further development and refinement of these indices is warranted.

The phytoplankton community-based indices developed here show promise as biological monitoring and lake trophic state assessment tools to aid area-wide planners responding to Section 208 of PL92-500.

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INTRODUCTION

As a direct result of an extensive investigation of phytoplankton relationships to environmental conditions several phytoplankton community-based indices have been developed for classifying lakes by trophic condition. The primary purpose of this report is to describe these indices and compare them with other techniques already in use. Thirty-eight indices and measurements, including 10 described here for the first time, are rated according to their ability to rank lakes by trophic state.

The need for classifying lakes was mandated by Congress with the passage of Public Law 92-500, Section 305, which declares that, "Each State shall prepare . . . an identification and classification according to eutrophic condition of all publicly owned fresh water lakes in such State." Numerous methods for trophic state determination had been developed prior to passage of PL 92-500 and further development has continued. Trophic classification techniques vary from complex multivariate models using combinations of biological, chemical, and physical data, to something as simple as Secchi disk measurement. Expensive and time consuming data gathering programs are generally associated with increased model complexity, which severely limits their utility for routine use.

CONCLUSIONS

1. Indices and measurements of trophic state that correlated well against the phosphorus standard did poorly against the chlorophyll *a* standard, and conversely, those that did well against chlorophyll *a* did poorly against total phosphorus. Only total Kjeldahl nitrogen had good agreement with both standards.

2. Several phytoplankton community-based trophic indices, introduced in this study, were shown to be more effective in trophically ranking a test set of 44 lakes, relative to chlorophyll *a* standard, than most of the widely-used trophic indices or indicator parameters tested.

3. Such widely-used biological indices as Palmer's Organic Pollution Index, Nygaard's Trophic State Indices, Shannon-Wiener's Phytoplankton Diversity Index, and Pielou's Evenness Component of Phytoplankton Diversity were generally ineffective for lake assessment.

4. Phosphorus loading models containing a phosphorus-retention component (Dillon and Larsen/Mercier) predicted the phosphorus-standard rank of the test lakes better than did the model (Vollenweider) not containing a phosphorus-retention component.

5. Secchi disk measurements provide a high measure of success in trophically ranking lakes relative to phosphorus levels.

6. Phosphorus loading models and Secchi Disk measurements did *not* successfully rank lakes relative to chlorophyll *a* levels thus limiting their abilities to predict a manifestation of eutrophication.

7. Total Kjeldahl nitrogen can provide effective trophic ranking relative to nutrient-manifestation criteria.

RECOMMENDATIONS

1. The strong performance of phytoplankton community-based indices suggests that the basic approach used is sound and that further development and refinement of these indices is warranted.

2. The phytoplankton data base, from which the index values are derived, should be expanded to provide more precise estimates of parameter values for optimal growth and hence improve the predictive reliability of the community-based indices.

3. Secchi disk transparency is recommended as a strong and simple surrogate parameter for the estimation of total phosphorus in lakes and of chlorophyll *a* in lakes with low inorganic turbidity levels.

4. Trophic classification "criteria" to be applied (whether nutrient- or response/manifestation-based) should be determined before selecting the most appropriate trophic index.

MATERIALS AND METHODS

Data used in the development of the new phytoplankton trophic state indices presented in this report are from the first five parts of the series "Phytoplankton Water Quality Relationships in U.S. Lakes" (Taylor et al. 1979a; Williams et al. 1979; Hern et al. 1979; Lambou et al. 1979; Morris et al. 1979). These publications present environmental statistics (ranges, means, and standard deviations for the major nutrients, chlorophyll a, temperature, pH, turbidity, Secchi depth, dissolved oxygen, alkalinity, and nitrogen to phosphorus ratio) based on photic zone data that were associated with the occurrences of 180 phytoplankton genera in 250 lakes from 17 States in the eastern and southeastern portion of the United States. The statistics associated with each genus are organized by season (spring, summer, and fall), and on an annual basis, addressing dominant and non-dominant occurrences within individual community structures.

Except for those indices and measurements of trophic state requiring annual data input, calculations of lake index values were based on summer data. Summer data were used because the biological response to nutrients (as measured by chlorophyll a) generally is greatest during that season. Data used in calculating the indices and measurements of trophic state other than the phytoplankton indices addressed here are from one or another of the following reports: Taylor et al. 1979a; individual lake reports, e.g., Report on Lake Lulu, Florida (EPA 1976); or from one of the State phytoplankton distribution summaries, e.g., Distribution of Phytoplankton in Alabama Lakes (Taylor et al. 1977). A complete list of "Distribution of Phytoplankton in Lakes" reports, one per State, is given in the bibliography.

Forty-four lakes and reservoirs were selected from the 250 sampled during 1973 to compare the 38 indices and measurements of trophic state. These lakes were selected on the basis of mean summer Secchi depth values so that the "test lakes" represent the full range of water clarity. Most of the lake data used in this report have been entered into STORET (STOrage and RETrieval), the U.S. Environmental Protection Agency's computer system which processes and maintains water quality data. Each lake was assigned a four-digit STORET number. The first two digits of the STORET number identify the State; the last two digits identify the lake. Lakes and reservoirs from each of the following 17 States are represented in the test set: Alabama, Delaware, Florida, Georgia, Illinois, Indiana, Kentucky, Maryland, Mississippi, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, and West Virginia.

In order to compare the various indices and measurements of trophic state, summer ambient mean total phosphorus and chlorophyll a values were used as standards of trophic state in the test lakes for ranking purposes.

Total phosphorus was chosen since it is generally considered to be the most important nutrient associated with the measurement of eutrophication in freshwater, while chlorophyll a concentration is considered the most reliable measurement of response to eutrophication. Williams et al. (1978) and Jones and Bachman (1976) support these choices for standards where strong correlations between total phosphorus and chlorophyll a were presented ($r=0.81$, $N=318$ and $r=0.95$, $N=146$, respectively). The former study used annual mean lake data while the latter was restricted to summer values.

Results from the calculation of each index and measurement of trophic state to be compared were used to rank the test lakes. Spearman's rank correlation coefficients (Siegel 1956) were calculated in order to compare the rankings resulting from the use of the 38 indices and measurements of trophic state with the rankings resulting from the use of the total phosphorus and chlorophyll a standards. In instances where tied observations were encountered, the procedures described by Siegel (1956) to "correct" for these ties were used. Lakes where data were missing for one of the 38 indices or measurements of trophic state were not used in the comparisons and calculation of the correlation for that index or measurement of trophic state.

DESCRIPTION OF TEST LAKES

The 44 test lakes ranked from lowest to highest Secchi disk transparency are presented in Table 1. Trophic class assignments from individual lake reports (e.g., Report on Lake Lulu, Florida [EPA 1976]) as well as eutrophic related lake problems, when known, are included.

Morphometric data for each of the test lakes (surface area, drainage area, mean depth, maximum depth, volume and retention time) are provided in Table 2 along with the National Eutrophication Survey Working Paper numbers for corresponding lake reports. A summary of the summer photic zone's physical and chemical characteristics for the test lakes is provided in Table 3. Mean summer photic zone values for chemical and physical parameters are given for each of the test lakes in Table 4.

TABLE 1. TEST LAKES RANKED BY MEAN SUMMER SECCHI DEPTH WITH COUNTY, STATE, STORET-CODE NUMBER, DATE SAMPLED, TROPHIC STATE, AND LAKE PROBLEMS INFORMATION

GROUPED BY SECCHI DEPTH	LAKE NAME	COUNTY(S)	STATE	STORET NUMBER	DATE	SECCHI DEPTH (INCHES)	TROPHIC STATE**	PROBLEM(S)**
LOW	Hovey Lake	Posey	Ind.	1849	08/11/73	6.0	E	A
	Loramie Lake	Shelby*	Ohio	3917	08/01/73	6.0	E	A,W
	Depue Lake	Bureau	Ill.	1752	08/07/73	6.0	E	F
	Highland Lake (Silver)	Madison	Ill.	1740	08/10/73	8.0	E	N.R.
	Slocum Lake	Lake	Ill.	1758	08/07/73	8.0	E	A
	Lake Lulu	Polk	Fla.	1227	09/06/73	9.0	E	A,W,F
	Lake Charleston	Coles	Ill.	1708	08/09/73	9.0	E	N.R.
	Fox Lake	Lake	Ill.	1755	08/07/73	9.0	E	N.R.
	Horseshoe Lake	Madison	Ill.	1766	08/10/73	10.0	E	A,F
	Lake Apopka	Orange*	Fla.	1202	09/06/73	11.6	E	A,W,F
	Lake Effie	Polk	Fla.	1209	09/05/73	12.0	H	A,W,F,D.O.
	Lake Hancock	Polk	Fla.	1217	09/04/73	12.0	E	A,W
MODERATELY LOW	Crab Orchard Lake	Jackson*	Ill.	1712	08/08/73	22.7	E	A
	Alligator Lake	Columbia	Fla.	1201	08/31/73	23.0	E	A,W
	Duhernal Lake	Middlesex	N.J.	3412	07/22/73	24.0	E	W
	Arkabutla Res.	Desoto*	Miss.	2801	08/28/73	25.3	E	N.R.
	Killen Pond	Kent	Del.	1002	07/20/73	26.0	E	A,W
	Saluda Lake	Greenville*	S.C.	4515	09/18/73	27.0	M	N.R.
MEDIUM	Lake Yale	Lake	Fla.	1246	09/06/73	40.0	E	A
	Lay Lake	Chilton*	Ala.	0106	08/29/73	41.0	E	N.R.
	Lake Eufaula	Quitman*	Ga.	1314	08/30/73	43.3	E	N.R.
	Lake Hickory	Alexander*	N.C.	3705	07/07/73	45.0	E	W
	Lake Chesdin	Dinwiddie	Va.	5111	07/13/73	47.3	E	N.R.
	Barren River Res.	Allen*	Ky.	2105	08/11/73	48.6	E	F
	Marsh Lake	Steuben	Ind.	1856	08/06/73	50.0	E	A
	Lake Moultrie	Berkley	S.C.	4512	07/09/73	52.7	E	N.R.
	East Loon Lake	Lake	Ill.	1757	08/07/73	54.0	E	A,W
	Lake Minnehaha	Orange	Fla.	1229	09/05/73	55.0	E	F
	Cherokee Lake	Jefferson*	Tenn.	4707	08/23/73	55.6	E	A,F
MODERATELY HIGH	Lake Murray	Lexington*	S.C.	4507	07/07/73	85.7	E	W
	Lake Maxinkuckee	Marshall	Ind.	1843	08/03/73	87.0	M	N.R.
	Martin Lake	Elmore*	Ala.	0107	08/25/73	90.6	M	N.R.
	Lake Hopatcong	Morris*	N.J.	3415	07/23/73	90.8	E	A,W,D.O.
	Tims Ford Res.	Moore*	Tenn.	4724	08/15/73	94.7	E	A
HIGH	Chatuge Lake	Towns	Ga.	1303	09/17/73	122.7	M	N.R.
	Dale Hollow Res.	Cumberland*	Ky.	2102	08/18/73	125.0	M	D.O.
	Tygard Res.	Taylor	W. Va.	5404	07/28/73	126.0	M	N.R.
	J. W. Flannagan Dam	Dickenson	Va.	5105	07/18/73	144.0	M	D.O.
	Deep Creek Lake	Garrett	Md.	2402	07/23/73	144.0	M	D.O.
	Liberty Res.	Carroll*	Md.	2403	07/20/73	150.0	M	A
	Lake Wallenpaupack	Pike	Pa.	4229	07/23/73	171.0	M	A,D.O.
	Wanaque Res.	Passaic	N.J.	3423	07/22/73	184.0	M	A
	Summersville Res.	Nicholas	W. Va.	5403	07/18/73	216.0	M	N.R.
	Harveys Lake	Luzerne	Pa.	4222	07/23/73	222.0	M	A,D.O.

*Extends into additional county(s)
**E = eutrophic, H = hypereutrophic, M = mesotrophic, A = algae blooms, W = nuisance weeds, F = fishkills, D.O. = dissolved oxygen depression, N.R. = none reported

TABLE 2. TEST LAKE MORPHOMETRY DATA, LAKE TYPE, AND NES WORKING PAPER NUMBER

STORET NUMBER	NAME	NES WORKING PAPER NO.	TYPE*	SURFACE AREA (km^2)	DRAINAGE AREA (km^2)	MEAN DEPTH (m)	MAXIMUM DEPTH (m)	VOLUME ($x10^6 m^3$)	RETENTION TIME (D=days, Y=years)
0106	LAY LAKE	230	I	48.56	23387.7	10.1	25.00	492.884	14 D
0107	MARTIN LAKE	231	I	157.83	7674.2	12.9	37.00	2036.007	176 D
1002	KILLEN POND	237	I	.30	46.4	1.5	2.70	.450	8 D
1201	ALLIGATOR LAKE	243	N	1.37	39.9	1.5	2.40	2.055	50 D
1202	LAKE APOPKA	244	N	125.40	476.6	1.7	5.50	213.180	2.5 Y
1209	LAKE EFFIE	224	N	.41	------	1.0	1.50	.410	----
1217	HANCOCK	---	N	18.29	------	1.0	1.5	18.29	96 D
1227	LAKE LULU	263	N	1.22	20.1	1.5	2.70	1.830	235 D
1229	LAKE MINNEHAHA	265	N	.39	4.3	3.0	4.00	1.170	97 D
1246	LAKE YALE	280	N	15.95	------	3.7	4.60	58.290	1.5 Y
1303	CHATUGE LAKE	286	I	28.94	489.5	10.6	36.90	306.764	296 D
1314	EUFAULA(WALTER F. GEORGE)	---	I	186.10	------	6.2	29.3	1154.192	47 D
1708	LAKE CHARLESTON	299	I	1.45	2035.7	.9	1.50	1.305	1 D
1712	CRAB ORCHARD LAKE	301	I	28.19	520.6	3.0	6.10	84.570	288 D
1740	HIGHLAND SILVER LAKE	306	I	2.99	122.0	4.2	7.30	12.558	189 D
1752	DEPUE LAKE	303	N	2.12	------	1.2	3.10	2.544	----
1755	FOX LAKE	305	N	6.76	3120.9	2.4	4.00	16.244	23 D
1757	EAST LOON LAKE	304	N	0.67	25.9	1.8	>6.4	1.229	89 D
1758	SLOCUM LAKE	316	N	.87	22.6	1.2	1.50	1.044	121 D
1766	HORSESHOE LAKE	308	N	8.78	83.1	2.1	0	18.193	420 D
1843	LAKE MAXINKUCKEE	335	N	7.54	35.5	7.3	26.80	55.042	6.7 Y
1849	HOVEY LAKE	329	N	.98	------	1.2	15.50	1.194	----
1856	MARSH LAKE	333	N	.23	38.6	6.1	11.60	1.403	45 D
2102	DALE HOLLOW RESERVOIR	352	I	108.62	2424.2	14.4	36.00	1569.000	1.2 Y
2105	BARREN RIVER RESERVOIR	350	I	40.47	2434.6	5.8	18.60	234.708	81 D
2402	DEEP CREEK LAKE	355	I	15.78	167.6	8.1	21.90	127.842	1.1 Y
2403	LIBERTY RESERVOIR	357	I	12.59	424.8	13.0	0	159.926	413 D
2801	ARKABUTLA RESERVOIR	359	I	48.04	2590.0	9.1	14.70	437.164	108 D
3412	DUNERNAL LAKE	365	I	.38	245.0	1.4	3.00	.532	2 D
3415	LAKE HOPATCONG	368	I	10.87	66.3	5.5	17.70	59.785	623 D
3423	WANAQUE RESERVOIR	376	I	9.35	234.1	11.3	27.40	105.655	218 D
3705	HICKORY LAKE	380	I	16.63	3392.9	9.5	25.90	157.000	33 D
3917	LAKE LORAMIE	405	I	3.18	201.2	1.5	5.10	4.770	29 D
4222	HARVEYS LAKE	419	N	2.67	17.3	11.0	29.30	29.370	1.6 Y
4229	LAKE WALLENPAUPACK	428	I	23.31	590.5	8.5	13.40	198.135	229 D
4507	LAKE MURRAY	436	I	205.58	6268.0	12.7	57.80	2608.000	348 D
4512	LAKE MOULTRIE	435	N	263.05	38850.0	5.7	23.00	1494.373	42 D
4515	SALUDA LAKE	438	I	2.25	753.7	4.0	12.20	9.000	6 D
4707	CHEROKEE LAKE	445	I	122.62	8878.5	14.9	49.70	1900.824	190 D
4724	TIMS FORD RESERVOIR	455	I	42.90	1370.1	15.2	43.60	749.968	379 D
5105	JOHN W FLANNAGAN RES.	463	I	4.63	572.4	18.0	46.00	83.340	118 D
5111	LAKE CHESDIN	458	I	12.95	3457.6	7.0	14.00	90.650	31 D
5403	SUMMERSVILLE RESERVOIR	469	I	11.02	2082.4	21.0	82.30	231.420	50 D
5404	TYGART RESERVOIR	470	I	7.08	3537.9	17.4	53.90	123.192	20 D

*I = artificial impoundment, N = natural lake

TABLE 3. SUMMARY OF THE SUMMER PHOTIC ZONE'S PHYSICAL AND CHEMICAL CHARACTERISTICS FOR THE TEST LAKES

Parameter	Number of Lake Values	Mean	Standard Deviation	Minimum Value	Maximum Value
Total Phosphorus (µg/l)	44	212	357	5	1600
Orthophosphorus (µg/l)	44	83	188	3	950
Nitrite-Nitrate-N (µg/l)	44	405	748	32	4275
Ammonia-N (µg/l)	44	133	125	36	720
Total Kjeldahl-N (µg/l)	44	1695	1890	228	7150
Secchi Depth (inches)	44	65	60	6	222
Chlorophyll a (µg/l)	44	70.5	125	1.4	595
Turbidity (% transmission)	43	66	34	4	121*
pH	44	7.8	1.0	5.4	10.1
Alkalinity (mg/l as $CaCO_3$)	44	76	78	10	293
Dissolved Oxygen (mg/l)	43	7.5	1.8	4.1	13.5
Temperature (degrees Celsius)	44	26.7	2.7	20.1	30.5
$\frac{\text{Inorganic N}^{**}}{\text{Total Phosphorus}}$ (N/P)	44	11.9	22.1	0.3	129.6

* One data point was recorded which exceeded a theoretical maximum of 106 percent light transmission in water with transmissometer calibrated for 100 percent transmission in air.

** Inorganic N = Nitrite-Nitrate-N + Ammonia-N.

TABLE 4. MEAN SUMMER TEST LAKE DATA FOR CHEMICAL AND PHYSICAL PARAMETERS

STORET NUMBER	DATE	TOTALP (mg/l)	ORTHOP (mg/l)	NO2NO3 (mg/l)	NH3 (mg/l)	KJEL (mg/l)	SECCHI (inches)	CHLA (µg/l)	TURB (% trans.)	PH	ALK (mg/l as $CaCO_3$)	DO (mg/l)	TEMP (°C)	N/P
0106	730829	0.039	0.016	0.087	0.043	0.556	41	10.7	91	7.4	54	4.9	29.8	3.4
0107	730825	0.013	0.009	0.047	0.054	0.507	91	5.8	92	7.0	12	7.3	28.9	9.4
1002	730720	0.216	0.046	1.500	0.190	1.200	26	101.2	.	8.4	25	8.1	25.4	7.8
1201	730831	0.429	0.237	0.152	0.112	2.925	23	155.8	79	9.3	52	9.9	29.4	0.7
1202	730906	0.161	0.032	0.193	0.140	4.850	12	77.9	35	8.8	127	8.8	28.9	2.3
1209	730905	1.600	0.950	0.210	0.200	5.700	12	595.0	11	7.2	123	.	28.3	0.3
1217	730904	0.607	0.135	0.425	0.250	6.350	12	166.8	7	10.1	73	10.2	28.9	1.2
1227	730906	1.120	0.590	0.190	0.170	7.150	9	456.6	42	9.5	73	7.2	28.5	0.3
1229	730905	0.022	0.013	0.050	0.050	1.200	55	11.9	88	8.0	39	7.8	30.2	4.5
1246	730906	0.027	0.018	0.062	0.054	1.375	40	56.2	84	8.6	108	8.2	29.2	4.4
1303	730917	0.017	0.006	0.034	0.038	0.329	123	5.8	95	6.2	11	7.0	25.5	5.0
1314	730830	0.030	0.008	0.164	0.092	0.667	43	11.8	81	7.9	20	6.9	29.0	8.0
1708	730809	0.164	0.076	4.275	0.095	1.150	9	15.3	18	7.9	237	6.8	25.8	26.6
1712	730808	0.184	0.043	0.124	0.135	2.328	23	106.8	29	8.4	59	8.0	29.2	2.3
1740	730810	0.258	0.060	0.946	0.307	1.639	8	5.4	19	7.3	63	4.1	26.2	5.3
1752	730807	1.030	0.556	1.720	0.720	3.700	6	112.7	4	8.3	240	7.4	30.5	2.4
1755	730807	0.322	0.119	0.172	0.195	2.917	9	108.8	46	8.7	239	6.7	25.1	1.1
1757	730807	0.073	0.029	0.113	0.233	1.633	54	28.0	74	8.2	172	4.4	24.0	4.7
1758	730807	0.882	0.385	0.175	0.150	6.250	8	312.0	26	9.3	293	13.5	25.2	0.4
1766	730810	0.256	0.026	0.252	0.180	4.300	10	258.7	5	9.3	49	8.6	28.3	1.9
1843	730803	0.014	0.003	0.063	0.065	0.400	87	5.8	92	8.4	140	8.5	23.9	9.0
1849	730811	0.868	0.037	0.150	0.130	3.600	6	206.7	5	8.0	141	7.4	30.1	0.3
1856	730806	0.115	0.080	0.072	0.142	1.150	50	19.4	92	8.1	275	11.7	21.5	1.9
2102	730818	0.013	0.007	0.121	0.059	0.417	125	6.4	95	7.3	64	7.9	28.4	15.2
2105	730811	0.049	0.014	0.202	0.090	0.539	49	9.5	89	8.3	74	6.5	28.3	5.8
2402	730723	0.011	0.007	0.252	0.041	0.262	144	7.9	95	6.6	11	8.1	23.9	26.4
2403	730720	0.015	0.006	1.825	0.070	0.546	150	7.7	91	8.1	25	8.1	23.4	129.6
2801	730828	0.058	0.009	0.073	0.089	1.050	25	4.9	76	6.8	26	4.2	28.5	2.8
3412	730722	0.179	0.026	0.975	0.505	1.200	24	8.6	57	5.4	10	6.5	22.9	8.3
3415	730723	0.025	0.008	0.051	0.077	0.570	91	10.0	94	6.9	23	6.6	25.0	5.2
3423	730722	0.014	0.008	0.032	0.036	0.311	184	8.2	93	7.1	13	8.9	24.9	5.2
3705	730707	0.034	0.006	0.107	0.121	0.467	45	6.3	87	7.4	12	6.7	26.6	7.3
3917	730801	0.204	0.016	1.200	0.175	2.250	6	103.4	13	8.3	130	7.2	24.4	6.7
4222	730723	0.009	0.005	0.070	0.071	0.300	222	7.3	88	7.1	25	8.6	20.1	15.7
4229	730723	0.013	0.006	0.055	0.057	0.333	171	8.8	87	6.7	17	8.1	24.2	8.8
4507	730707	0.021	0.006	0.076	0.085	0.462	86	7.1	86	7.5	18	6.8	29.6	9.1
4512	730709	0.025	0.005	0.087	0.089	0.762	53	7.6	95	7.5	25	7.2	30.1	7.2
4515	730918	0.073	0.007	0.140	0.070	0.475	27	1.4	61	6.4	12	7.0	21.4	4.0
4707	730823	0.037	0.018	0.355	0.099	0.643	56	13.6	83	8.5	78	7.1	26.8	13.8
4724	730815	0.025	0.008	0.084	0.066	0.333	95	7.7	94	7.9	o1	4.5	28.1	6.2
5105	730718	0.011	0.006	0.089	0.059	0.411	144	10.6	81	8.3	27	8.9	27.2	15.9
5111	730713	0.040	0.007	0.088	0.119	0.844	47	14.9	61	7.4	39	5.7	28.2	6.0
5403	730718	0.010	0.007	0.507	0.064	0.308	216	13.4	121*	7.0	11	7.8	25.6	57.2
5404	730728	0.005	0.003	0.266	0.044	0.228	126	1.5	93	6.5	13	7.6	26.8	62.0

* One data point was recorded which exceeded a theoretical maximum of 106 percent light transmission in water with transmissometer calibrated for 100 percent transmission in air.

DESCRIPTIONS OF INDICES AND MEASUREMENTS OF TROPHIC STATE

Selection of indices and measurements of trophic state compared in this report was restricted by the data base available from our lake sampling program (U.S. Environmental Protection Agency 1975). Consequently, several approaches could not be tested, e.g., Shannon and Brezonik's (1972) principle component trophic state index for lack of "light box" productivity data and Pearsall's cation ratio, and biomass measurements such as dry and ash-free weights.

SINGLE PARAMETER MEASUREMENTS OF TROPHIC STATE

Secchi Depth

Secchi depth (SECCHI) is a measure of water transparency, the value being modified by particulate and dissolved matter in the water acting to block the transmission of light. Phytoplankton and/or suspended sediments are important factors affecting the measurement, e.g. an algal bloom will result in a relatively low Secchi depth reading. Mean summer Secchi depth values (Table 4) for the test lakes were ranked low to high ranging from 6 to 222 inches* (Appendix A1).

Carlson's Trophic State Indices

Carlson (1977) developed a trophic state index that is a transformation of Secchi disk transparency such that each major unit on the scale has half the transparency of the next lower unit. This index will be identified as Carlson's Secchi Depth Index and is derived from Secchi disk transparency as follows:

$$\text{Carlson's Secchi Depth Index} = 10(6 - \log_2 \text{SECCHI}),$$

where Secchi depth values are in meters (m) (the mean Secchi depth values listed in the tables of our report are in inches). The scale of values is such that zero has a transparency of 64 m, greater than the highest value reported for any lake in the world. The next major unit, 10, would have a transparency half that found at zero, or 32 m, and so on up to and beyond a Carlson's Secchi Depth Index value of 100 which represents a transparency of 0.062 m.

Furthermore, Carlson used empirically determined relationships between total phosphorus (TOTALP) and transparency, and between chlorophyll a (CHLA) and transparency, to arrive at approximately the same trophic state index

*All Secchi disk measurements were made in inches.

regardless of whether Secchi depth, total phosphorus or chlorophyll *a* was the variable measured.

Chlorophyll *a* values for each of the test lakes (Table 4) were converted to Carlson's Secchi Depth Index using Carlson's (1977) formula, which is as follows:

$$\text{Carlson's Chlorophyll } a \text{ Index} = 10\left(6 - \log_2 7.7 \frac{1}{\text{CHLA } 0.68}\right)$$

where chlorophyll *a* values are in µg/l.

Total phosphorus values (Table 4) for each of the test lakes were converted to Carlson's Secchi Depth Index using Carlson's (1977) formula, which is as follows:

$$\text{Carlson's Total Phosphorus Index} = 10\left(6 - \log_2 48 \frac{1}{\text{TOTALP}}\right)$$

where total phosphorus values are in µg/l.

The results of Carlson's three indices are ranked from high to low and presented in Appendix A2. These indices may not agree with each other in lakes where biological productivity is limited by non-nutrient related factors such as temperature or toxic chemicals. Carlson (1977) states that differences in his indices can be used to direct research towards understanding the divergence from otherwise strong relationships.

Total Phosphorus

Total phosphorus (TOTALP) is a measure of all phosphorus including dissolved and particulate forms of inorganic and biological origin. Mean summer TOTALP values (Table 4) for the test lakes were ranked high to low, ranging from 1600 to 5 µg/l (Appendix A1).

Chlorophyll a

Chlorophyll *a* (CHLA) is a widely used and accepted index of algal biomass. CHLA has been found to be highly correlated with phosphorus, particularly in lakes and reservoirs with retention times greater than 14 days (Williams et al. 1978; Lambou et al. 1976). The correlation does not hold for systems with less than 14-day retention times in which inadequate time is available for full response. Mean summer CHLA values (Table 4) for the test lakes were ranked high to low, ranging from 595.0 to 1.4 µg/l (Appendix A1).

Total Kjeldahl Nitrogen

Total Kjeldahl nitrogen (KJEL) is a measure of ammonia plus all organically derived nitrogen. KJEL can be used as an indicator of biomass since ammonia usually accounted for less than 10 percent of the values. KJEL has been demonstrated to be highly correlated with CHLA in eastern U.S. lakes

(Williams et al. 1978). The KJEL value for any given lake would also include KJEL from allochthonous sources, including sewage treatment plants. Mean summer KJEL values (Table 4) for the test lakes were ranked from high to low, ranging from 7150 to 228 µg/l (Appendix A1).

Specific Conductance

Specific conductance (COND) is a measure of a water's capacity to convey an electric current at 25° C and is related to the total concentration of ionic substances in the water (APHA 1971). COND can be used to estimate total dissolved solids (APHA 1971) which has been shown by Beeton (1965) to be correlated with eutrophication. Freshly distilled water would have a COND value between 0.5 and 2 µmho. Mean summer COND values for the test lakes were ranked high to low, ranging from 877 to 23 µmho (Appendix A1).

Algal Assay Control Yield

Algal assay control yield (AACY) is a measure of the primary production potential within a water sample. It was determined as part of an assay procedure designed to establish nitrogen or phosphorus limitation in the test lakes (U.S. EPA 1971). Samples for the assays were collected during the spring since lake waters are thought to have their greatest algal growth potential at that time. Theoretically, it should provide an estimate of the maximum algal biomass producible in lakes under near optimal conditions. AACY values for the test lakes were ranked high to low, ranging from 25.2 to 0.1 mg/l dry weight (Appendix A3).

Phytoplankton Concentration

Phytoplankton concentration was determined by counting cells, filaments, or colonies depending upon the cellular organization of each species. Presumably, water with high nutrients can support larger populations than water with low nutrients. As such, phytoplankton concentrations for the test lakes were ranked from high to low, ranging from 166,883 to 183 algal units per ml (A.U./ml) (Appendix A4).

Number of Phytoplankton Species

The number of phytoplankton species is perhaps the simplest measure of diversity in a lake. The number of phytoplankton species estimated for the test lakes were ranked from high to low, ranging from 56 to 6 taxa per lake (Appendix A4).

Number of Phytoplankton Species (modified)

This modification of the previous measurement does not include those species encountered only in preliminary sample examination or once in the enumeration process (phytoplankton sample analyses include a preliminary examination for species identification, followed by a separate procedure for enumerating the organisms by species). This measurement is included to assess the effects of eliminating rare species (Pielou 1975) upon diversity estimates.

The number of phytoplankton species (modified) estimated for the test lakes were ranked from high to low, ranging from 32 to 2 (Appendix A4).

Phytoplankton Biovolume

Phytoplankton biovolume is an estimate of biomass. Biovolumes calculated for the individual components (species) within each sample were tallied to provide an estimate of the biovolume occupied by the total phytoplankton population. Phytoplankton biovolume calculations were based upon our measurements of algal unit size and concentration. Phytoplankton biovolumes for the test lakes were ranked from high to low, with biovolume values ranging from 1496.15×10^6 to 0.16×10^6 μ^3/ml (Appendix A4).

MULTIPLE PARAMETER MEASUREMENTS OF TROPHIC STATE

Models Predicting Ambient Lake Phosphorus Concentrations

Three models used to predict mean ambient lake phosphorus concentrations at equilibrium are compared in this report. These are the Vollenweider (1975), Dillon (1975), and Larsen and Mercier (1976) models. The Dillon (1975) and Larsen and Mercier (1976) models are modifications of Vollenweider's (1968) original phosphorus loading-mean depth-concept.

These models have been widely accepted and used to indicate the degree of eutrophy of lakes and evaluate the level of phosphorus loading to lakes. Dillon (1975) utilized phosphorus areal loading (L), the retention coefficient for phosphorus (R), the hydraulic flushing rate (P), and mean depth (Z) in a plot of the form

$$\frac{L\ (1-R)}{P}$$

versus Z, to estimate trophic state. Vollenweider (1975) revised his original formula to include T, hydraulic residence time, so that areal phosphorus loading (L) is plotted against mean depth (Z) divided by T. Larsen and Mercier (1976) provide an alternative (to the prior loading concepts) which avoids the criticism of Edmondson (1970) that the effect of an increasing phosphorus load upon a lake depends, in part, upon whether that increase results from increases in influent flows, concentrations, or both. The Larsen and Mercier formula plots mean tributary phosphorus concentration against phosphorus retention coefficient, called R experimental, computed in the same way as Dillon's R:

$$R = \frac{\text{Total phosphorus leaving}}{\text{Total phosphorus entering}}$$

It is interesting to note that in applying the above-mentioned formulas, each of the authors elected to use levels of 10 and 20 μg/l of ambient lake phosphorus to divide lakes into the three standard trophic classifications--oligotrophic, mesotrophic, and eutrophic.

Solution analyses based on 20 µg/l were employed to place the three formulas on an equivalent basis by dividing the appropriate theoretical minimum eutrophic "loading" rate (i.e., that which would produce an ambient lake concentration of 20 µg/l) for a given lake into the actual "loading" rate determined for that lake. Hereafter, these ratios will be referred to as the Vollenweider, Dillon, and Larsen and Mercier "trophic ratios." Trophic ratios which exceed or equal 1.0 represent eutrophic loading, whereas trophic ratios extending from 0.5 to less than 1.0 represent mesotrophic loadings and trophic ratios below 0.5 represent oligotrophic loadings, regardless of the formula employed (Hern et al. 1978). Lakes were ranked from high to low by trophic ratio with values ranging from: 75.62 to 0.18 for the Vollenweider trophic ratio; 74.00 to 0.38 for the Dillon trophic ratio; and 259.90 to 0.39 for the Larsen and Mercier trophic ratio (Appendix A5).

Nitrogen to Phosphorus Ratio

The nitrogen to phosphorus ratio (N/P) is a measure of the relative concentrations of inorganic nitrogen (NO_2NO_3 and NH_3) to total phosphorus. Various estimates have been proposed as to what constitutes that ratio of nitrogen to phosphorus at which the addition of either results in the limitation by the other. Such estimates have been reported as low as 5/1 and as high as 30/1 or more, by weight, generally centering about 12/1 to 14/1. These are in reasonable agreement with theoretical needs based upon stoichiometric equations of algal constituents (Vollenweider 1968). Evaluation of eastern lakes (Lambou et al. 1976; Williams et al. 1978) suggests that low N/P ratios reflect, in most cases, high ambient phosphorus levels, rather than low ambient inorganic nitrogen levels. As such, N/P ratios would be expected to mimic, to a large extent, the ambient total phosphorus levels of the systems tested. The N/P ratio values (Table 4) for the test lakes were ranked low to high, ranging from 0.3 to 129.6 (Appendix A1).

Nygaard's Trophic State Indices

Nygaard (1949) developed five phytoplankton indices (myxophycean, chlorophycean, diatom, euglenophyte, and compound) of trophic state under the assumption that certain algal groups are indicative of various levels of nutrient enrichment. His assumption is that Cyanophyta, Euglenophyta, centric diatoms, and members of the Chlorococcales are found in waters that are eutrophic, while desmids and many pennate diatoms generally cannot tolerate high nutrient levels and so are found in oligotrophic waters.

In applying Nygaard's indices, the number of taxa in each major group is determined from the species list for each summer sample. The ratios of these groups give numerical values which are used as biological indices of water richness. The five indices and the ranges of values established by Nygaard for each trophic state are presented in Table 5. Wherever the numerator or denominator was zero for any given index, a useful value could not be calculated and that lake was eliminated from the test.

Values were ranked from high to low for each of Nygaard's indices (Appendix A5). Ranges for each of the indices are given in Table 5.

TABLE 5. NYGAARD'S TROPHIC STATE INDICES ADAPTED FROM HUTCHINSON (1967)

Index	Calculation	Oligotrophic	Eutrophic	Test Lake Ranges	
				Min	Max
Nygaard's Myxophycean Index	$\frac{\text{Myxophyceae}}{\text{Desmideae}}$	0.0 - 0.4	0.1 - 3.0	0.67	9.00
Nygaard's Chlorophycean Index	$\frac{\text{Chlorococcales}}{\text{Desmideae}}$	0.0 - 0.7	0.2 - 9.0	0.33	15.50
Nygaard's Diatom Index	$\frac{\text{Centric Diatoms}}{\text{Pennate Diatoms}}$	0.0 - 0.3	0.0 - 1.75	0.07	5.00
Nygaard's Euglenophyte Index	$\frac{\text{Euglenophyta}}{\text{Myxophyceae + Chlorococcales}}$	0.0 - 0.2	0.0 - 1.0	0.03	1.20
Nygaard's Compound Index	$\frac{\text{Myxophyceae + Chlorococcales + Centric Diatoms + Euglenophyta}}{\text{Desmideae}}$	0.0 - 1.0	1.2 -25	2.00	38.00

Palmer's Organic Pollution Indices

Palmer (1969) analyzed reports from 165 authors and developed two algal pollution indices (genus and species) for use in rating water samples with high organic pollution. Two lists of organic pollution-tolerant forms were prepared, one containing 20 genera, the other, 20 species (Tables 6 and 7). Each form was assigned a pollution index number ranging from 1 for moderately tolerant forms to 6 for extremely tolerant forms. Palmer based the index numbers on occurrence records and on findings of especially high tolerance of organic pollution reported by other researchers.

In analyzing a water sample, any of the 20 genera or species of algae present in concentrations of 50/ml or more are recorded. The pollution index numbers of the algae present are totaled, providing a genus score (Palmer's Genus Index) and a species score (Palmer's Species Index). Palmer determined that a score of 20 or more for either index can be taken as evidence of high organic pollution, while a score of 15 to 19 is taken as probable evidence of high organic pollution. Lower figures suggest that the organic pollution of the sample is not high, that the sample is not representative, or that some substance or factor interfering with algal persistence is present and active.

In this study, each index was applied to summer phytoplankton data, where the total of the pollution index numbers were used to rank the test lakes from high to low (Appendix A3). Genus index values ranged from 25 to 1 while species index values ranged from 9 to 1. Since the explanation for absence of all index taxa (species or genus) in a sample may be due to factors other than organic-pollution, lakes scoring zero were eliminated from the rank correlations.

TABLE 6. ALGAL GENUS POLLUTION INDEX (Palmer 1969)

Genus	Pollution Index
Anacystis	1
Ankistrodesmus	2
Chlamydomonas	4
Chlorella	3
Closterium	1
Cyclotella	1
Euglena	5
Gomphonema	1
Lepocinclis	1
Melosira	1
Micractinium	1
Navicula	3
Nitzschia	3
Oscillatoria	5
Pandorina	1
Phacus	2
Phormidium	1
Scenedesmus	4
Stigeoclonium	2
Synedra	2

TABLE 7. ALGAL SPECIES POLLUTION INDEX (Palmer 1969)

Species	Pollution Index
Ankistrodesmus falcatus	3
Arthrospira jenneri	2
Chlorella vulgaris	2
Cyclotella meneghiniana	2
Euglena gracilis	1
Euglena viridis	6
Gomphonema parvulum	1
Melosira varians	2
Navicula cryptocephala	1
Nitzschia acicularis	1
Nitzschia palea	5
Oscillatoria chlorina	2
Oscillatoria limosa	4
Oscillatoria princeps	1
Oscillatoria putrida	1
Oscillatoria tenuis	4
Pandorina morum	3
Scenedesmus quadricauda	4
Stigeoclonium tenue	3
Synedra ulna	3

Phytoplankton Species Diversity

"Information content" of biological samples is being used commonly by biologists as a measure of diversity. Diversity in this connection means the degree of uncertainty attached to the specific identity of any randomly selected individual. The greater the number of taxa and the more equal their proportions, the greater the uncertainty, and hence, the diversity (Pielou 1966). There are several methods of measuring diversity, e.g., the formulas given by Brillouin (1962) and Shannon and Weaver (1963). The method that is appropriate depends on the type of biological sample on hand. We are testing phytoplankton diversity as a method for establishing lake trophic state.

Pielou (1966) classifies the types of biological samples and gives the measure of diversity appropriate for each type. Our phytoplankton samples are what she classifies as larger samples (collections in Pielou's terminology) from which random subsamples can be drawn. According to Pielou, the average diversity per individual (H) for these types of samples can be estimated

from the Shannon-Wiener formula (Shannon and Weaver 1963):

$$H = - \sum_{i=1}^{S} P_i \log_x P_i$$

where P is the proportion of the ith taxon in the sample, which is calculated from n_i/N; n_i is the number of individuals per milliliter of the ith taxon; N is the total number of individuals per ml; and S is the total number of taxa. We used $\log_2$ in our calculations. Values of H for the test lakes were ranked from low to high, ranging from 0.67 to 4.31 (Appendix A3).

Evenness Component of Phytoplankton Diversity

The evenness component of phytoplankton diversity (J) is a ratio which shows how closely H (diversity) approaches the maximum diversity (MaxH) in a sample. J is approximated by the formula H/MaxH, where MaxH is estimated from $\log_2$ S (S is the total number of taxa in the sample) (Pielou 1966). The possible range of values for J is 0 to 1, where values near zero are indicative of the least evenly distributed communities and values nearing 1 are indicative of the most evenly distributed communities i.e., those approaching maximum diversity. In using this index, we are testing the relationship between J and trophic state. Values of J for the test lakes were ranked from high to low, ranging from 0.79 to 0.14 (Appendix A3).

CERL Trophic State Index

The Corvallis Environmental Research Laboratory (CERL) developed a numerical trophic index designed to provide a more realistic assignment of trophic condition than the relatively inflexible categorizations of oligotrophic, mesotrophic, eutrophic, or hypereutrophic (U.S. EPA 1974). The CERL TSI is a multi-variate index in which a percentile ranking procedure is used. In this procedure, for each of the unweighted parameters used, the percentage of the 250 lakes (lakes sampled by the U.S. EPA during 1973) exceeding Lake X in that parameter, e.g., level of chlorophyll *a*, was determined. The final lake ranking value (CERL TSI) is simply the sum of the percentile ranks for each of the parameters used.

Parameters used in calculating the index include: annual median total phosphorus, inorganic nitrogen (NO_2-NO_3 + NH_3), dissolved orthophosphorus, annual mean Secchi disk, chlorophyll *a*, and the minimum dissolved oxygen value recorded during the year. The values for Secchi disk transparency and minimum dissolved oxygen are subtracted from fixed values so that all parameters contribute in a positive way to the ranking. The units are of no consequence since all index values are expressed as a percentage. The complete list of CERL TSI values for lakes sampled in 1973 has not been published.

With the CERL TSI, high numbers correspond to the oligotrophic end of the spectrum while low numbers correspond to the eutrophic end. CERL TSI values for the test lakes were ranked from low to high, ranging from 76 to 499 (Appendix A1).

Multivariate Trophic State Indices

Two multivariate trophic state indices were developed through principal components analysis, a mathematical technique that can be used to reduce the dimensionality of a multivariate system by representing the original attributes as functions of the attributes. The basic objective is to summarize most of the variance in the system of lake water quality variables by using a lesser number of "artificial" variates (i.e., principal components). The first index, Boland PCl_1, incorporated the trophic indicators: chlorophyll *a*, conductivity, inverse Secchi disk transparency, total phosphorus, total organic nitrogen and algal assay control yield, using annual mean values. The second index, Boland PCl_2, resulted from an analysis of similar parameters except that total Kjeldahl nitrogen was substituted for total organic nitrogen and summer mean values were used instead of annual data. Algal assay control yield was determined on spring samples in both cases. These analyses were calculated in a manner similar to that of Boland (1976). In each case, the data values were first transformed using natural logarithms and then the correlation (R) matrix was developed. Next, the first normalized eigenvector was extracted and evaluated for each of the lakes, resulting in 342 and 44 trophic index values, one per lake for Boland PCl_1 and Boland PCl_2, respectively (Boland PCl_1 was calculated with a data base of 342 lakes). The numeric value defines where along the first principal axis the lake is located. The larger the number, the closer the water body is to the eutrophic end of the water quality scale.

The numerical values resulting from both Boland PCl_1 and Boland PCl_2 were ranked from high to low, ranging from 4.83 to -2.54 and 4.36 to -2.75, respectively (Appendix A6).

PROPOSED PHYTOPLANKTON INDICES TO TROPHIC STATE

The magnitude and scope of our study provided a unique opportunity to examine the physical and chemical conditions associated with phytoplankton occurrence. The study resulted in more than 2.5 million physical, chemical, and biological data points from 815 lakes throughout the 48 contiguous states. Although the lake sampling took 4 years to complete (1972-1975), a consistent methodology was maintained for most aspects of the program throughout the study period. All of the data, including phytoplankton species lists and counts, are in computer files where statistical data analyses are performed most efficiently.

Analyses of information contained in the phytoplankton environmental summaries (Taylor et al. 1979a; Williams et al. 1979; Hern et al. 1979; Lambou et al. 1979; Morris et al. 1979) that were calculated from data collected for 250 lakes during the 1973 sampling year, are presented by Taylor et al. (1979b). Trends identified in that report led to the exploration of methods for application of the knowledge to biological trophic classification of lakes and reservoirs.

Two important findings were included in the report. First, most phytoplankton genera were found to occur over wide ranges of conditions, effectively eliminating most of the genera from consideration as indicator organisms. Second, central tendencies expressed as mean parameter values (e.g., Scenedesmus, with 50 dominant sample occurrences, had a mean CHLA value of 60.4 µg/l) showed trends that reflected trophic association, if not preference. Genera that, as dominants, were associated with relatively high mean CHLA values were similarly related to other parameters, e.g., high TOTALP, ammonia and 1/Secchi depth values. Similar relationships occurred at the opposite (low mean parameter value) end of the scale as well. Since data are available describing the central tendencies of more than 80 genera that attained dominance in at least one sample, it seems reasonable to explore the possibilities of using that information for classifying lake waters.

While no universal agreement on an entirely suitable definition of eutrophication has been reached (Stewart and Rohlich 1967; and Brezonik et al. 1969), or even agreement on parameters to measure, most workers would agree that eutrophication is a complex process of lake evolution tied directly to nutrient enrichment. To the phytoplankton, eutrophication is just one more of many changes continuously occurring in their environment. As lake conditions change, so the phytoplankton change; communities constantly adjust to take advantage of available conditions. Phytoplankton can be considered integrators of numerous physical and chemical conditions found in lake waters, and that integration is reflected in community structure. The approach presented here attempts to analyze specific communities, in terms of our knowledge about the generic components, to arrive at a biological statement of trophic state.

Development of Phytoplankton Trophic Values

The basic element in our approach to the development of phytoplankton indices was the assignment of "trophic values" to each genus based upon mean parameter values associated with the dominant occurrences of each genus as found in the 250 lakes sampled during spring, summer, and fall of 1973 (see Hern et al. 1979; Lambou et al. 1979, Morris et al. 1979, and Williams et al. 1979). Trophic values assigned to genera on the basis of relationships established from analysis of a large data base were applied to the taxa occurring within the lake to be trophically evaluated. Mean parameter values for dominant occurrences of phytoplankton forms were used in establishing trophic values because they approximate advantageous conditions for the growth of these forms.

All genus-trophic-values used in formulating the phytoplankton trophic indices are presented in Table 8. The genus-trophic-values, total phosphorus (TOTALP), chlorophyll a (CHLA), and total Kjeldahl nitrogen (KJEL) in Table 8, are simply mean photic zone values associated with the dominant occurrences of each genus. TOTALP/CONC, CHLA/CONC, and KJEL/CONC were calculated by dividing the TOTALP, CHLA, and KJEL values by the corresponding mean cell count. Also given in Table 8 is a genus-trophic-multivariate-value (MV) calculated for each genus using the following formula:

$$MV = \text{Log TOTALP} + \text{Log CHLA} + \text{Log KJEL} - \text{Log SECCHI}$$

TABLE 8. TROPHIC VALUES OF SELECTED GENERA BASED UPON MEAN PARAMETER VALUES ASSOCIATED WITH THEIR OCCURRENCE AS DOMINANTS

GENUS	DOMINANT OCCURRENCES	TOTALP	CHLA	KJEL	TOTALP CONC	CHLA CONC	KJEL CONC	MV
Achnanthes	6	29	11.5	734	.027	.001	.689	3.53
Actinastrum	2	56	3.5	594	.142	.009	1.508	3.62
Anabaena	33	183	19.7	1015	.098	.011	.545	4.82
Anabaenopsis	7	70	32.9	1393	.008	.004	.165	5.01
Ankistrodesmus	9	75	17.9	573	.082	.020	.626	4.25
Anomoeoneis	3	10	5.4	364	.005	.002	.166	2.32
Aphanizomenon	41	147	37.6	1437	.058	.015	.569	5.18
Aphanocapsa	4	242	21.1	1427	.034	.003	.200	5.04
Aphanothece	3	65	32.4	1493	.009	.004	.203	4.98
Arthrospira	2	51	21.0	1227	.022	.009	.519	4.37
Asterionella	36	36	9.6	491	.023	.006	.310	3.87
Attheya	1	70	1.4	473	1.892	.038	12.784	3.23
Binuclearia	1	42	6.7	425	.038	.006	.384	3.37
Botryococcus	2	56	10.3	1049	.013	.002	.250	4.20
Carteria	2	509	44.5	1513	.176	.015	.523	6.04
Ceratium	2	140	5.2	1046	3.784	.141	28.270	3.84
Chlamydomonas	4	847	55.1	3143	.162	.011	.601	6.75
Chlorella	3	70	53.1	991	.015	.012	.215	5.13
Chromulina	1	8	10.0	348	.008	.010	.336	2.46
Chroococcus	19	163	46.6	1630	.028	.008	.283	5.37
Chroomonas	1	116	32.9	1421	.084	.024	1.032	5.50
Chrysocapsa	1	10	7.9	261	.015	.012	.380	2.16
Chrysococcus	2	1580	75.0	4631	.197	.009	.576	7.32
Closterium	4	20	19.8	698	.007	.007	.249	3.60
Coelastrum	6	60	13.4	1208	.077	.017	1.549	4.36
Coelosphaerium	6	44	11.7	888	.097	.026	1.965	3.82
Coscinodiscus	3	138	62.7	1267	.053	.024	.488	5.25
Cosmarium	3	14	9.9	586	.003	.002	.115	3.27
Crucigenia	2	361	11.8	1048	.696	.023	2.019	4.67

Continued

TABLE 8. TROPHIC VALUES OF SELECTED GENERA BASED UPON MEAN PARAMETER VALUES ASSOCIATED WITH THEIR OCCURRENCE AS DOMINANTS (Continued)

GENUS	DOMINANT OCCURRENCES	TOTALP	CHLA	KJEL	TOTALP CONC	CHLA CONC	KJEL CONC	MV
Cryptomonas	72	115	16.5	798	.102	.015	.711	4.53
Cyclotella	83	185	29.9	1053	.073	.012	.418	4.10
Dactylococcopsis	58	178	25.0	1041	.026	.004	.153	5.05
Dictyosphaerium	1	18	10.8	949	.050	.030	2.658	3.45
Dinobryon	31	27	8.1	594	.043	.013	.938	3.16
Euglena	8	318	24.5	1481	.190	.015	.884	5.70
Eunotia	1	178	8.6	1199	3.296	.159	22.204	4.88
Fragilaria	45	64	17.5	843	.019	.005	.247	4.13
Glenodinium	4	8	6.4	403	.020	.016	1.025	2.34
Gloeocystis	6	35	10.9	639	.057	.018	1.034	3.50
Gloeothece	2	9	4.0	412	.069	.031	3.169	2.23
Golenkinia	2	615	26.9	1040	.195	.009	.330	5.60
Gomphonema	1	10	7.4	782	.019	.014	1.507	--
Gomphosphaeria	4	25	8.3	1270	.123	.041	6.225	3.65
Gymnodinium	2	9	2.8	256	.053	.016	1.506	1.68
Kirchneriella	8	139	7.6	755	.123	.007	.669	4.15
Lyngbya	99	99	29.5	1488	.008	.002	.115	4.98
Mallomonas	6	87	6.0	642	.798	.055	5.890	3.62
Melosira	255	94	18.1	774	.034	.006	.277	4.49
Merismopedia	22	183	33.6	1387	.059	.011	.444	5.34
Mesostigma	1	57	12.8	571	.131	.029	1.310	4.04
Micractinium	1	101	52.8	1098	.041	.021	.446	5.22
Microcystis	53	148	37.5	1457	.056	.014	.547	5.27
Mougeotia	2	76	29.2	990	.058	.022	.757	5.09
Navicula	6	74	8.2	490	.127	.014	.838	3.93
Nitzschia	29	92	26.5	883	.042	.012	.402	4.78
Oocystis	5	38	14.0	1098	.005	.002	.157	3.97
Oscillatoria	105	125	39.2	1356	.014	.004	.150	5.27
Peridinium	6	16	8.4	595	.054	.029	2.024	3.01
Phacus	2	2523	22.8	4049	3.955	.036	6.346	7.59

Continued

TABLE 8. TROPHIC VALUES OF SELECTED GENERA BASED UPON MEAN PARAMETER VALUES ASSOCIATED WITH THEIR OCCURRENCE AS DOMINANTS (Continued)

GENUS	DOMINANT OCCURRENCES	TOTALP	CHLA	KJEL	TOTALP CONC	CHLA CONC	KJEL CONC	MV
Phormidium	3	172	113.2	1955	.102	.067	1.164	5.77
Pinnularia	1	4	0.5	264	.400	.050	26.400	0.78
Raphidiopsis	45	106	30.5	1073	.010	.003	.097	4.88
Rhizosolenia	1	31	15.9	1161	.014	.007	.519	4.19
Roya	1	7	2.4	332	.030	.010	1.437	1.68
Scenedesmus	50	351	60.4	1826	.058	.010	.303	6.01
Schroederia	2	17	4.1	552	.063	.015	2.060	2.54
Selenastrum	1	99	9.3	465	.116	.011	.546	4.13
Spermatozoopsis	2	65	8.8	1631	.085	.012	2.132	4.13
Sphaerellopsis	1	57	6.4	532	.594	.067	5.542	3.56
Sphaerocystis	2	46	11.3	1274	.032	.008	.897	4.23
Sphaerozosma	1	13	16.6	750	.002	.003	.128	3.61
Spondylosium	1	21	6.4	599	.058	.018	1.659	--
Staurastrum	1	13	16.6	750	.004	.006	.251	3.61
Stauroneis	1	79	1.9	557	9.875	.238	69.625	3.62
Stephanodiscus	73	166	37.0	1112	.045	.010	.304	5.27
Synedra	48	82	19.0	797	.027	.006	.261	4.42
Synura	1	131	8.9	1449	1.056	.072	11.685	5.11
Tabellaria	20	22	7.7	455	.015	.005	.307	2.86
Tetraëdron	5	18	5.2	384	.040	.012	.859	2.66
Tetrastrum	1	28	6.9	625	.043	.011	.963	3.53
Trachelomonas	4	97	6.0	867	.292	.018	2.611	4.38
GENERAL CATEGORIES								
centric diatoms	32	142	24.9	1000	.033	.006	.234	4.97
pennate diatoms	17	254	46.8	1615	.036	.007	.227	5.81
flagellate	108	154	13.7	882	.075	.007	.427	4.55
flagellates	199	99	14.6	749	.054	.008	.411	4.30
chrysophytan	5	54	10.5	635	.010	.002	.118	3.73

where TOTALP, CHLA, KJEL, and SECCHI are again, mean values associated with dominant occurrences of each genus.

Application of Phytoplankton Trophic Values

We have formulated 10 phytoplankton trophic state indices based upon varying application procedures using the genus-trophic-values given in Table 8. These indices can be placed in 2 categories, those using cell counts and those not using cell counts in their application. The indices not using cell counts are the simplest to calculate, and will be described first.

Phytoplankton Trophic State Index (TSI) Calculations Without Cell Counts

The four phytoplankton trophic state indices not requiring cell counts in their application are designated as TOTALP(PD), CHLA(PD), KJEL(PD), and MV(PD) where TOTALP, CHLA, KJEL, and MV refer to the genus-trophic-values given in Table 8, and PD (phytoplankton-dominant) indicates that the phytoplankton index is calculated on the basis of the dominant genera (rather than all genera detected) in a test lake. These indices are calculated according to the following generalized formula:

$$\text{Phytoplankton TSI} = \sum_{i=1}^{n} V_i \Big/ n \qquad (1)$$

where Phytoplankton TSI is the phytoplankton trophic state index for the lake, n is the number of dominant genera in the sample (concentration $\geq$ 10 percent of the total sample concentration), and V is the trophic value, for each dominant genus in the sample. A demonstration of the procedure for calculating the TOTALP(PD) phytoplankton TSI on Fox Lake, Illinois (STORET No. 1755) using formula 1 is given in Table 9.

Three genera are listed as dominants in Table 9, i.e., Aphanizomenon, Melosira, and Stephanodiscus. The sum of the TOTALP trophic values (V) for each of the dominant genera is divided by n, (i.e., 3) the number of dominant genera in the sample, to arrive at a TOTALP(PD) phytoplankton TSI for the lake equal to 135.6.

TOTALP(PD), CHLA(PD), and KJEL(PD) TSI values for the test lakes were ranked from high to low, ranging from 268 to 10, 75.0 to 5.4, and 1706 to 364, respectively (Appendix A7). MV(PD) TSI values for the test lakes were ranked from high to low, ranging from 5.64 - 2.32 (Appendix A8).

TABLE 9. PROCEDURE FOR CALCULATING THE TOTALP(PD) PHYTOPLANKTON TSI USING FOX LAKE, ILLINOIS, AS AN EXAMPLE

Dominant Genera in Fox Lake (STORET No. 1755)	Percent Occurrence	V (TOTALP, from Table 8)
Aphanizomenon	41.2	147
Melosira	15.9	94
Stephanodiscus	15.5	166
		Sum Total = 406
	TOTALP(PD) phytoplankton TSI = $\frac{406}{3}$ = 135.6	

Phytoplankton Trophic State Index Calculations With Cell Counts

Two variations in the application of each of the genus-trophic-values designated as TOTALP/CONC, CHLA/CONC, and KJEL/CONC (Table 8) have been proposed for use as phytoplankton trophic state indices. One variation uses the entire phytoplankton community in its calculation while the second variation uses only the dominant phytoplankton community in its calculation.

Total Community Phytoplankton Trophic State Index

The three phytoplankton trophic state indices requiring cell count data, which are calculated using the entire phytoplankton community, are designated TOTALP/CONC(P), CHLA/CONC(P), and KJEL/CONC(P), where TOTALP/CONC, CHLA/CONC, and KJEL/CONC refer to the genus-trophic-values given in Table 8, and P (phytoplankton) indicates that the indices are calculated on the basis of the entire phytoplankton community. These indices are calculated according to the following formula:

$$\text{Phytoplankton TSI} = \sum_{i=1}^{n} V_i C_i \qquad (2)$$

where phytoplankton TSI is the phytoplankton trophic state index for the lake, n is the number of genera in the sample, V is the appropriate trophic-value for each genus, and C is the concentration of the genus in the sample. A demonstration of the procedure for calculating the TOTALP/CONC(P) phytoplankton TSI using formula 2 is presented in Table 10.

TABLE 10. PROCEDURE FOR CALCULATING THE TOTALP/CONC(P) PHYTOPLANKTON TSI USING FOX LAKE, ILLINOIS, AS AN EXAMPLE

Genera Counted in Fox Lake, Illinois (STORET No. 1755)	Percent of Count	C (Algal Units per ml)	V (TOTALP/CONC, Table 8)	V x C
Anabaena	3.7	237	.098	23
Aphanizomenon	41.2	2631	.058	153
Closterium	0.3	22	.007	0
Crucigenia	0.3	22	.696	15
Cyclotella	1.0	65	.073	5
Flagellates	0.3	22	.054	1
Glenodinium	1.7	108	.020	2
Gomphosphaeria	1.7	108	.123	13
Melosira	15.9	1014	.034	34
Microcystis	5.1	324	.056	18
Oocystis	4.1	259	.005	1
Oscillatoria	4.1	259	.014	4
Phormidium	0.3	22	.102	2
Scenedesmus	3.7	237	.058	14
Sphaerocystis	0.7	43	.032	1
Stephanodiscus	15.5	992	.045	45
Synedra	0.3	22	.027	1
				SUM TOTAL = 332

TOTALP/CONC(P) phytoplankton TSI = 332

In the example (Table 10) the concentration (C) of each genus in the sample, regardless of dominant status, is multiplied by its TOTALP/CONC trophic value (V). The sum of all such products (332) is the TOTALP/CONC(P) phytoplankton TSI for Fox Lake.

TOTALP/CONC(P), CHLA/CONC(P), and KJEL/CONC(P) values for the test lakes were ranked from high to low, ranging from 17,332 to 10 (Appendix A7), 12,160 to 2 (Appendix A7), and 62,081 to 132 (Appendix A8), respectively.

Dominant Community Phytoplankton Trophic State Index

The three phytoplankton trophic state indices requiring cell count data, which are calculated using only dominant genera, are designated TOTALP/CONC (PD), CHLA/CONC(PD), and KJEL/CONC(PD), where TOTALP/CONC, CHLA/CONC, and KJEL/CONC refer to the genus-trophic-values given in Table 8, and PD (phytoplankton-dominant) indicates that the phytoplankton index is calculated on the basis of the dominant genera (rather than on all genera detected) in a test lake. These indices are calculated using formula 2.

This group of phytoplankton trophic state indices differs from the last group in that only trophic-values (V) and concentrations (C) for dominant genera in the sample are used. A demonstration of the procedure for calculating the TOTALP/CONC(PD) phytoplankton TSI using formula 2 is presented in Table 11.

TABLE 11. PROCEDURE FOR CALCULATING THE TOTALP/CONC(PD) PHYTOPLANKTON TSI USING FOX LAKE, ILLINOIS, AS AN EXAMPLE

Dominant Genera in Fox Lake, Illinois (STORET No. 1755)	Percent of Count	C (Algal Units Per ml)	V (TOTALP/CONC Table 8)	V x C
Aphanizomenon	41.2	2631	.058	153
Melosira	15.9	1041	.034	34
Stephanodiscus	15.5	992	.045	45
			SUM TOTAL =	232

TOTALP/CONC(PD) phytoplankton TSI = 232

In the example (Table 11) the concentration (C) of each dominant genus in the sample is multiplied by its TOTALP/CONC trophic-value (V). The sum of all such products (232) is the TOTALP/CONC(PD) phytoplankton TSI for Fox Lake.

TOTALP/CONC(PD), CHLA/CONC(PD), and KJEL/CONC(PD) values for the test lakes were ranked from high to low, ranging from 7,438 to 4, 797 to 2, and 27,947 to 132, respectively (Appendix A8).

RESULTS AND DISCUSSION

Values calculated for each index and measurement of trophic state and the corresponding rankings for each of the test lakes are presented in Appendices A1 through A8. The ranking of lakes by each of the indices is compared in turn against that produced by trophic ranking standards, total phosphorus and chlorophyll *a*. Tables 12 and 13 list the various indices and measurements of trophic state by the strength of their relationship (Spearman rank correlation coefficient) with the total phosphorus and chlorophyll *a* standards.

The Larsen and Mercier, Dillon, and Vollenweider trophic ratios predict ambient lake phosphorus levels, which is supported by their high rank correlations with the total phosphorus standard (r_s = 0.94, 0.92, and 0.82, respectively). However, they do not predict relative chlorophyll *a* levels as well (r_s = 0.64, 0.50, and 0.49, respectively). In fact, *no* indices or measurements or trophic state did well in matching the trophic rankings based upon chlorophyll *a*. Total phosphorus- and chlorophyll *a*-based rankings showed only modest agreement (r_s = 0.71), which indicates that there may indeed by differences in relative trophic ranking whether primary nutrients or biological manifestations are used as the ranking mechanism.

One of the primary reasons for these differences becomes evident when the relative ranking successes of Secchi disk transparency and Secchi-based indices such as Carlson's Secchi Depth index are evaluated. Note how effectively Secchi depth was able to rank the test lakes relative to the phosphorus ranking (r_s = 0.93) (Table 12). Simple transformation of the Secchi depth values to $\log_2$ does not, of course, alter the relative ranking and an identical r_s is therefore obtained by the Carlson scheme. However, the Secchi-based trophic rankings, when compared with the chlorophyll *a* standard rank, show similar performance drop-offs to those noted with phosphorus loading trophic ratios.

Phosphorus is a component of biological particulates, such as phytoplankton, which reduce light penetration as their density (and hence the phosphorus concentration) increases. However, phosphorus is also an important component of most *inorganic* particulates found in natural waters. As a result, decreased light penetration in water, regardless of the turbidity source, is nearly always accompanied by concomitant increases in total phosphorus levels. At the same time, it is well known that decreased light penetration, particularly in heavily sediment-laden waters, can result in low phytoplankton populations and hence low chlorophyll *a* levels. Where phytoplankton growth is limited by restricted light penetration, we often encounter the paradox of negative correlation between chlorophyll *a* and total phosphorus. In addition to reducing light penetration, inorganic suspensoids often contain

TABLE 12. INDICES AND MEASUREMENTS OF TROPHIC STATE RANKED BY THEIR CORRELATION WITH SUMMER AMBIENT MEAN PHOSPHORUS LEVELS

INDEX	SPEARMAN'S RANK CORRELATION COEFFICIENT (rs)	t-value	DEGREES OF FREEDOM
Larsen & Mercier Trophic Ratio	.94	14.438 **	37
Boland PCl_2	.93	14.437 **	30
Secchi Depth	.93	15.872 **	42
Carlson's Secchi Depth Index	.93	15.872 **	42
CERL TSI	.92	14.800 **	42
Dillon Trophic Ratio	.92	13.035 **	33
Boland PCl_1	.91	9.299 **	18
Total Kjeldahl Nitrogen	.91	14.200 **	42
Vollenweider Trophic Ratio	.82	8.486 **	34
Algal Assay Control Yield	.80	7.139 **	29
N/P Ratio	.77	7.930 **	42
+ Multivariate Algal Index (PD)	.72	6.818 **	42
Chlorophyll a	.71	6.462 **	42
Carlson's Chlorophyll a Index	.71	6.462 **	42
+ KJEL/CONC(PD)	.68	5.948 **	42
+ TOTALP/CONC(PD)	.67	5.916 **	42
Specific Conductance	.66	5.697 **	42
+ KJEL(PD)	.66	5.647 **	42
+ CHLA(PD)	.64	5.337 **	42
+ TOTALP/CONC(P)	.63	5.302 **	42
+ KJEL/CONC(P)	.62	5.152 **	42
+ CHLA/CONC(PD)	.62	5.048 **	42
+ CHLA/CONC(P)	.61	4.944 **	42
+ TOTALP(PD)	.58	4.628 **	42
Phytoplankton Concentration	.55	4.221 **	42
Palmer's Genus Index	.54	3.935 **	38
Phytoplankton Biovolume	.52	3.928 **	42
Nygaard's Compound Index	.47	2.873 **	30
Nygaard's Chlorococcalean Index	.45	2.721 *	30
Number of phytoplankton species	.35	2.435 *	42
Number of phytoplankton species (modified)	.31	2.117 *	42
Nygaard's Myxophycean Index	.24	1.314	29
Nygaard's Euglenophycean Index	.19	0.914	23
Phytoplankton Species Diversity (H)	-.18	-1.206	42
Evenness Component of Phytoplankton Diversity (J)	-.15	0.960	42
Nygaard's Diatom Index	.12	0.740	39
Palmer's Species Index	-.06	-0.231	14

\+ New biological indices based on the phytoplankton community structure.
** significant at the 0.01 level.
* significant at the 0.05 level.

TABLE 13. INDICES AND MEASUREMENTS OF TROPHIC STATE RANKED BY THEIR CORRELATION WITH SUMMER AMBIENT MEAN CHLOROPHYLL a LEVELS

INDEX	SPEARMAN'S RANK CORRELATION COEFFICIENT (rs)	t-value	DEGREES OF FREEDOM
+ KJEL/CONC(PD)	.79	8.258 **	42
Total Kjeldahl Nitrogen	.78	8.177 **	42
+ CHLA/CONC(PD)	.76	7.631 **	42
+ CHLA/CONC(P)	.75	7.304 **	42
+ KJEL/CONC(P)	.75	7.260 **	42
Phytoplankton Concentration	.72	6.740 **	42
Specific Conductance	.72	6.648 **	42
+ TOTALP/CONC(PD)	.71	6.610 **	42
+ TOTALP/CONC(P)	.71	6.530 **	42
Total Phosphorus	.71	6.460 **	42
Carlson's Total Phosphorus Index	.71	6.460 **	42
+ CHLA(PD)	.70	6.290 **	42
CERL TSI	.68	5.967 **	42
+ Multivariate Algal Index (PD)	.67	5.797 **	42
Phytoplankton Biovolume	.66	5.737 **	42
Boland PCl_2	.64	4.525 **	30
Larsen & Mercier Trophic Ratio	.64	5.049 **	37
+ KJEL(PD)	.63	5.256 **	42
Boland PCl_1	.62	3.393 **	18
N/P Ratio	.61	5.030 **	42
Secchi Depth	.60	4.846 **	42
Carlson's Secchi Depth Index	.60	4.846 **	42
Algal Assay Control Yield	.56	3.643 **	29
Palmer's Genus Index	.53	3.860 **	38
+ TOTALP(PD)	.50	3.765 **	42
Dillon Trophic Ratio	.50	3.336 **	33
Vollenweider Trophic Ratio	.49	3.280 **	34
Nygaard's Chlorococcalean Index	.46	2.833 **	30
Number of phytoplankton species (modified)	.37	2.601 *	42
Number of phytoplankton species	.35	2.426 *	42
Nygaard's Compound Index	.32	1.876	30
Nygaard's Euglenophycean Index	-.30	1.509	23
Nygaard's Myxophycean Index	.26	1.445	29
Evenness Component of Phytoplankton Diversity (J)	-.25	1.698	42
Palmer's Species Index	.04	0.158	14
Nygaard's Diatom Index	-.04	0.234	39
Phytoplankton Species Diversity (H)	.01	0.035	42

\+ New biological indices based on the phytoplankton community structure.
* Significant at 0.05 level.
** Significant at 0.01 level.

high levels of phosphorus in a biologically unavailable form. In such cases, the biological response (chlorophyll *a*) will be lower than that predicted from total phosphorus levels. These factors therefore contribute to diminish the effective "interchangeability" of Carlson TSI's (Secchi-, Total phosphorus- and chlorophyll *a*-based).

Had the test lakes not been comprised of a broad range of lake types, including some highly turbid (low Secchi disk) lakes, we might expect the ranking by total phosphorus to be in close agreement with that obtained with chlorophyll *a*. There is abundant evidence for the high correlations between phosphorus and chlorophyll *a* in lakes not carrying a heavy silt load (Sakamoto 1966, Dillon and Rigler 1974, Jones and Bachmann 1976, and others). We do not feel that extrapolation of such relationships to populations of lakes carrying heavy inorganic particulate loads (river-run reservoirs, shallow wind-driven lakes, etc.) is appropriate (see Hern et al. 1978).

In addition to Secchi depth, only Kjeldahl nitrogen, among the other single-parameter "indices," provides noteworthy rank correlation with the phosphorus standard rank ($r_s = 0.91$). Indeed, Kjeldahl nitrogen and Kjeldahl-based phytoplankton indices largely dominate the "successful" trophic rankings relative to that of the chlorophyll *a* standard. The high rank correlation of total Kjeldahl nitrogen to chlorophyll *a* ($r_s = 0.78$) is not unexpected as the chlorophyll-containing autotrophs are primary sources of the organic nitrogen in surface waters. Williams et al. (1978) tested a large set of lake data (277 lakes) and found the correlation between Kjeldahl nitrogen and chlorophyll *a* to be $r = 0.82$. Kjeldahl nitrogen may prove to be a very important parameter in refining nutrient/response relationships in surface waters.

Other single parameter measurements of trophic state that may have some utility or potential application, although not highly ranked, include chlorophyll *a* (and its Carlson-transformed analog) ($r_s = 0.71$ against phosphorus standard); conductivity ($r_s = 0.66$ against phosphorus, 0.72 against chlorophyll *a*); phytoplankton concentration ($r_s = 0.55$ against phosphorus, 0.72 against chlorophyll *a*); and phytoplankton biovolume ($r_s = 0.52$ against phosphorus, 0.66 against chlorophyll *a*).

The performances of phytoplankton concentration and biovolume relative to the chlorophyll *a*-based standard ($r_s = 0.72$ and 0.66, respectively) may, at first, appear disappointingly low. However, when the wide variation in the phytoplankton cells and colonies counted is considered, the total count (concentration) performance is actually quite good. That phytoplankton concentration exceeded biovolume in ability to rank the test lake set, relative to both of the standards, is rather surprising and may reflect, in part, relative differences in the chlorophyll *a* contents of various phytoplankton taxa.

Conductivity was rather effective in predicting the trophic ranking of lakes by the chlorophyll *a* standard ($r_s = 0.72$) and slightly less so for the phosphorus-standard ranking ($r_s = 0.66$). The relative success of this estimate of total dissolved solids (reported by Beeton, 1965 to be positively related to trophic condition) suggests that soluble nutrients generally vary

with the total dissolved load. The relationship to total phosphorus is not stronger and reflects differences among waters in both the ionic constituents and the fractions of the phosphorus in bound and soluble form.

The use of Algal Assay Control Yield to trophically rank the test lake gave creditable agreement with the phosphorus-standard rank (rs = 0.80), but gave disappointing results against chlorophyll a (rs = 0.56). This response may represent the antithesis of the nutrient/response relationship problem previously discussed. Under conditions of the assay, yields should approach theoretical optima based upon nutrient availability. Therefore, water samples, from lakes in which the maximum response was not reached because of light limitation, are essentially freed to achieve their yield potentials. As a result, the strength of the relationship between natural systems and assay yields is diminished.

The three multivariate indices utilizing various combinations of physical and/or chemical data, e.g., Boland's PCl_1 and PCl_2, and the CERL TSI, were, as expected, among the better performers in relation to the phosphorus-standard lake ranking. All three utilize ambient total phosphorus and one or more additional highly phosphorus-correlated parameters. However, while the three approaches also share chlorophyll a as a common component, the best performance among these indices against the chlorophyll a-standard ranking (CERL TSI), yielded an rs of only 0.68.

The success of N/P ratio in ranking the test lakes relative to the phosphorus-standard rank (rs = 0.77) was expected, based upon knowledge of the overall population of lakes from which the test set was extracted. Virtually all of the eastern and southeastern lakes with low N/P ratios had an abundance of phosphorus rather than a paucity of nitrogen (see Williams et al. 1978). Inclusion of a higher percentage of low-nutrient, low N/P ratio lakes, as found in the western U.S., would likely diminish the strength of the N/P ratio ranking noted here.

Some of the indices were especially ineffective at trophically ranking the test lakes. This group includes some widely-used indices based upon the nature of, and/or the distributional patterns of phytoplankton species, genera, or higher taxonomic groupings.

Nygaard's indices assume a degree of uniformity within various phytoplankton taxonomic groups that extensive phytoplankton analyses at EMSL-Las Vegas have not substantiated (Hern et al. 1979, Lambou et al. 1979, Morris et al. 1979, Williams et al. 1979, Taylor et al. 1979b). In many cases, within-group variability (the range of environmental conditions associated with the group's occurrence) was so great that it masked any real differences that might have existed among groups.

The poor performance of Palmer's Genus and Species Indices in trophically ranking the test lakes was not surprising. First, the information used to compile the listings of pollution tolerant genera and species came from a broad range of sources and geographical areas and the reported data were not independently confirmed. Second, although the indices have been extrapolated for trophic evaluations in the past, Palmer's intent was to provide indices

for rating water samples with high organic pollution levels. Although organic pollution and nutrient enrichment, in many waters, may arise from a common source this does not imply they are synonymous.

The application of diversity and "evenness" indices to trophic ranking of lakes, while not new, has had a mixed reception. The performance of the Shannon-Wiener Diversity Index and Pielou's Evenness Component of Diversity in this study suggests that they offer little with respect to trophic ranking of lakes (r_s = -0.18 and -0.15, respectively with the phosphorus-standard ranking; r_s = 0.01 and -0.25, respectively with the chlorophyll a-standard ranking).

While Rawson (1956) and others have suggested the variety of planktonic forms as a useful character in trophic classification, neither the number of phytoplankton species nor the modification thereof was effective in trophically ranking lakes as measured by either standard ranking in this study. The modification, eliminating the rarer species components of the community from consideration, had little effect on the rank predictability relative to either ranking-standard. The total number of species identified in a sample is largely dependent upon the competence of the worker and the length of time used in the analysis. As pointed out by Kalff and Knoechel (1978), a sanitation engineer examining receiving water is likely to recognize about a dozen taxa; a competent taxonomist will recognize 10 or 20 times that number. In a given lake, over a period of weeks, nutrient enrichment can support a rich, diverse phytoplankton population with great numbers of taxa represented; generate a massive, essentially-unispecific algal bloom; and/or crash to low numbers in few representative taxa. That neither total numbers nor various measures of diversity, based upon instantaneous samples, provide effective trophic ranking of lakes should therefore be of no surprise.

The phytoplankton-based trophic indices developed in this study are preliminary and little attempt has been made to refine them for predictive capabilities. Even so, their general performance in trophically ranking lakes relative to the chlorophyll a-standard was a very pleasant surprise. Six of the top 10 indices, including 4 of the top 5 positions, are represented by these new indices (r_s values ranging from 0.71 to 0.79). Those indices applied to the dominant phytoplankton community components (>10 percent of the total cell count in a sample) generally had higher correlations than the analogous indices applied to all phytoplankton community components, although the differences were small. The inclusion of cell count as a component in index computation improved index performance [e.g., CHLA/CONC(PD) yielded an r_s of 0.76 versus CHLA(PD) with r_s = 0.70].

The performance of the new indices in trophically ranking the test lakes relative to the phosphorus-standard rank was not impressive, although one of the indices [Multivariate Algal Index (PD)] slightly outperformed the ranking accomplished by chlorophyll a (r_s = 0.72 versus 0.71, respectively). Considering the broad ranges of environmental conditions noted for most genera studied (Taylor et al. 1979b), even this level of performance is extremely encouraging and suggests that further refinement and development are warranted.

Comparing the overall performance of the new indices against other phytoplankton-based indices (Palmer's, Nygaard's, Diversity Indices) suggests that the new indices can perform with distinction in competition with the best-known and most widely-used indices for ranking lakes relative to the standard of trophic manifestation, chlorophyll a. Further testing of the indices against totally independent sets of lakes is planned to verify the method.

While the general performance of the more useful indices presented in this report is higher with respect to predicting phosphorus- than chlorophyll a-based trophic rankings, it is important to differentiate between these ranking standards. Phosphorus represents an important driving variable in the process of eutrophication in most freshwaters, while chlorophyll a represents an index to the manifestations of that process. Phosphorus levels represent a potential for growth that may or may not be realized in a natural system (see Williams et al. 1978). Chlorophyll a levels represent, to a large degree, the realization of this potential for growth. The selection of a standard that best represents the eutrophic component of greatest import to the researcher, monitor, or watershed manager can in turn dictate the selection of a trophic index that best meets specific requirements.

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APPENDIX A

The following tables (Appendices A1-A8) contain all of the index and measurement of trophic state values and corresponding rank positions for each of the 44 test lakes. The lakes are listed according to the rank order, high to low, of the mean summer lake total phosphorus concentrations.

In some instances two or more lakes had the same index or measurement of trophic state value, in which cases rank values were assigned according to the method described by Siegle (1956) for tied observations, e.g., under TOTALP in Appendix A1 two lakes (STORET numbers 1757 and 4515) had TOTALP values of 73; each was assigned the average rank (18.5) of the consecutive rank positions (18 and 19). Lakes where data were missing for one of the 38 indices or measurements of trophic state, were not used in the comparisons and calculation of the correlation for that index or measurement of trophic state.

Appendix A1: Test Lakes with Index Values and Measurements of Trophic State and with Ranks for the following: TOTALP, CHLA, SECCHI DEPTH, N/P, KJEL, Specific Conductance, and CERL TSI. 44

Appendix A2: Test Lakes with Trophic Index Values and Ranks for the following: Carlson's Chlorophyll *a*, Carlson's Total Phosphorus, Carlson's Secchi Depth 45

Appendix A3: Test Lakes with Index Values and Measurements of Trophic State and with Ranks for the following: Palmer's Genus and Species Indices, H, J, Algal Assay Control Yield. . . 46

Appendix A4: Test Lakes with Measurements of Trophic State and Ranks for the following: Number of Phytoplankton Species, Number of Phytoplankton Species (modified), Phytoplankton Concentration, Phytoplankton Biovolume. . . 47

Appendix A5: Test Lakes with Trophic Index Values and Ranks for the following Indices: Nygaard's Myxophycean, Chlorococcalean, Euglenophycean, Diatom, and Compound . . 48

Appendix A6: Test Lakes with Trophic Index Values and Ranks for the following Indices: Boland PCl_1, Boland PCl_2, Vollenweider Trophic Ratio, Dillon Trophic Ratio, and Larsen-Mercier Trophic Ratio 49

Appendix A7: Test Lakes with Trophic Index Values and Ranks for the following Indices: TOTALP(PD), CHLA(PD), KJEL(PD) TOTALP/CONC(P), and CHLA/CONC(P) 50

Appendix A8: Test Lakes with Trophic Index Values and Ranks for the following Indices: KJEL/CONC(P), TOTALP/CONC(PD), CHLA/CONC(PD), KJEL/CONC(PD), and Multivariate Algal Index (PD). 51

APPENDIX A1. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: TOTALP, CHLA, SECCHI DEPTH, N/P, KJEL, SPECIFIC CONDUCTANCE, AND CORVALLIS TSI

STORET NUMBER	TOTALP (µg/l)	RANK	CHLA (µg/l)	RANK	SECCHI DEPTH (inches)	RANK	N/P	RANK	KJEL (µg/l)	RANK	SPECIFIC CONDUCTANCE (µmho)	RANK	CERL TSI	RANK
1209	1600	1	595.0	1	12.0	11.5	0.3	2	5700	4	353	11	122	3
1227	1120	2	456.6	2	9.0	7	0.3	2	7150	1	328	13.5	76	1
1752	1030	3	112.7	8	6.0	2	2.4	12	3700	7	877	1	119	2
1758	882	4	312.0	3	8.0	4.5	0.4	4	6250	3	755	2	182	10
1849	868	5	206.7	5	6.0	2	0.3	2	3600	8	437	8	195	12
1217	608	6	166.8	6	12.0	11.5	1.2	7	6350	2	300	15	198	13
1201	429	7	155.8	7	23.0	14	0.7	5	2925	9	178	22	158	7
1755	322	8	108.9	9	9.0	7	1.1	6	2917	10	576	4	172	9
1740	258	9	5.4	41	8.0	4.5	5.3	22	1639	13	224	19	151	5
1766	256	10	258.7	4	10.0	9	1.9	8.5	4300	6	613	3	200	14
1002	216	11	101.2	12	26.0	17	7.8	29	1200	17	150	26	127	4
3917	204	12	103.4	11	6.0	2	6.7	26	2250	12	404	9	156	6
1712	184	13	106.8	10	22.7	13	2.3	10.5	2328	11	274	16	231	15
3412	179	14	8.6	28	24.0	15	8.3	31	1200	17	141	27	300	21
1708	164	15	15.3	17	9.0	7	26.6	41	1150	19.5	548	5	162	8
1202	161	16	77.9	13	11.6	10	2.3	10.5	4850	5	388	10	234	16.5
1856	115	17	19.4	16	50.0	25	1.9	8.5	1150	19.5	525	6	234	16.5
1757	73	18.5	28.0	15	54.0	27	4.7	18	1633	14	475	7	274	20
4515	73	18.5	1.4	44	27.0	18	4.0	15	475	31	27	43	399	31
2801	58	20	4.9	42	25.3	16	2.8	13	1050	21	78	33	193	11
2105	49	21	9.5	26	48.6	24	5.8	23	539	29	199	20	333	24
5111	40	22	14.9	18	47.3	23	6.0	24	844	22	92	31	304	22
0106	39	23	10.7	23	41.0	20	3.4	14	556	27	171	24	263	19
4707	37	24	13.6	19	55.6	29	13.8	36	643	25	243	17	234	16.5
3705	34	25	6.3	37	45.0	22	7.3	28	467	32	57	38	356	26
1314	30	26	11.8	22	43.3	21	8.0	30	667	24	69	36	322	23
1246	27	27	56.2	14	40.0	19	4.4	16	1375	15	328	13.5	393	30
4512	25	29	7.6	33	52.7	26	7.2	27	763	23	72	34	420	32.5
3415	25	29	10.0	25	90.8	33	5.2	20.5	570	26	161	25	381	28
4724	25	29	7.7	31.5	94.7	34	6.2	25	333	37.5	130	28	359	27
1229	22	31	11.9	21	55.0	28	4.5	17	1200	17	192	21	439	38
4507	20	32	7.1	35	85.7	30	9.1	34	462	33	64	37	382	29
1303	17	33	5.8	39	122.7	35	5.0	19	329	39	23	44	456	39
2403	15	34	7.7	31.5	150.0	40	129.6	44	546	28	96	29	351	25
3423	14	35.5	8.2	29	184.0	42	5.2	20.5	311	40	71	35	466	41.5
1843	14	35.5	5.8	39	87.0	31	9.0	33	400	36	348	12	499	44
2102	13	38	6.4	36	125.0	36	15.2	37	417	34	172	23	466	41.5
4229	13	38	8.8	27	171.0	41	8.8	32	333	37.5	49	41	437	37
0107	13	38	5.8	39	90.6	32	9.4	35	507	30	38	42	423	34
5105	11	40.5	10.6	24	144.0	38.5	15.9	39	411	35	232	18	434	36
2402	11	40.5	7.9	30	144.0	38.5	26.4	40	262	43	53	39	426	35
5403	10	42	13.4	20	216.0	43	57.2	42	308	41	50	40	420	32.5
4222	9	43	7.4	34	222.0	44	15.7	38	300	42	80	32	473	43
5404	5	44	1.5	43	126.0	37	62.0	43	228	44	95	30	465	40
N	44		44		44		44		44		44		44	

APPENDIX A2. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: CARLSON'S CHLOROPHYLL a INDEX, CARLSON'S TOTAL PHOSPHORUS INDEX, AND CARLSON'S SECCHI DEPTH INDEX

STORET NUMBER	CARLSON'S CHLOROPHYLL a INDEX	RANK	CARLSON'S TOTAL PHOSPHORUS INDEX	RANK	CARLSON'S SECCHI DEPTH INDEX	RANK
1209	93.23	1	110.59	1	77.14	11.5
1227	90.63	2	105.44	2	81.29	7
1752	76.90	8	104.23	3	87.14	2
1758	86.89	3	102.00	4	82.99	4.5
1849	82.85	5	101.77	5	87.14	2
1217	80.75	6	96.63	6	77.14	11.5
1201	80.08	7	91.60	7	67.75	14
1755	76.57	9	87.46	8	81.29	7
1740	41.10	41	84.26	9	82.99	4.5
1766	85.05	4	84.15	10	79.77	9
1002	75.85	12	81.70	11	65.98	17
3917	76.06	11	80.87	12	87.14	2
1712	76.38	10	79.39	13	67.94	13
3412	51.66	28	78.99	14	67.14	15
1708	57.31	17	77.73	15	81.29	7
1202	73.28	13	77.46	16	77.63	10
1856	59.64	16	72.61	17	56.55	25
1757	63.24	15	66.05	18.5	55.44	27
4515	33.85	44	66.05	18.5	65.44	18
2801	46.14	42	62.73	20	66.38	16
2105	52.64	26	60.30	21	59.96	24
5111	57.05	18	57.37	22	57.35	23
0106	53.80	23	57.00	23	59.41	20
4707	56.16	19	56.24	24	55.02	29
3705	48.61	37	55.03	25	58.07	22
1314	54.76	22	53.22	26	58.62	21
1246	70.08	14	51.70	27	59.77	19
4512	50.45	33	50.59	29	55.79	26
3415	53.14	25	50.59	29	47.94	33
4724	50.58	31.5	50.59	29	47.34	34
1229	54.85	21	48.74	31	55.18	28
4507	49.78	35	47.37	32	48.78	30
1303	47.80	39	45.03	33	43.60	35
2403	50.58	31.5	43.22	34	40.70	40
3423	51.19	29	42.22	35.5	37.75	42
1843	47.80	39	42.22	35.5	48.56	31
2102	48.76	36	41.15	38	43.33	36
4229	51.89	27	41.15	38	38.81	41
0107	47.80	39	41.15	38	47.98	32
5105	53.71	24	38.74	40.5	41.29	38.5
2402	50.83	30	38.74	40.5	41.29	38.5
5403	56.01	20	37.37	42	35.44	43
4222	50.19	34	35.85	43	35.05	44
5404	34.53	43	27.37	44	43.22	37
N	44		44		44	

APPENDIX A3. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: PALMER'S GENUS AND SPECIES, H, J, AND ALGAL ASSAY CONTROL YIELD

STORET NUMBER	PALMER'S GENUS INDEX	RANK	PALMER'S SPECIES INDEX	RANK	H	RANK	J	RANK	ALGAL ASSAY CONTROL YIELD (mg/l dry weight)	RANK
1209	21	6.5	6	5.5	3.92	43	0.68	9.5	-	-
1227	5	27	4	10	2.34	14	0.57	22	25.2	1
1752	23	3.5	4	10	3.73	42	0.68	9.5	-	-
1758	6	22.5	-	-	0.67	1	0.14	44	20.7	3.5
1849	23	3.5	7	3	2.94	29	0.51	31.5	4.7	9
1217	11	16	4	10	2.64	19.5	0.54	26.5	16.7	5
1201	13	12	2	14	4.31	44	0.79	1	-	-
1755	8	19	2	14	2.77	23	0.52	29	-	-
1740	2	34.5	-	-	2.91	27	0.63	18	23.3	2
1766	24	2	5	7	2.96	30	0.51	31.5	20.7	3.5
1002	12	13.5	4	10	1.70	3	0.51	31.5	15.9	6
3917	25	1	7	3	3.13	32	0.54	26.5	15.5	7
1712	21	6.5	9	1	3.41	35	0.64	16	-	-
3412	5	27	-	-	2.67	21	0.62	20	0.1	26.5
1708	6	22.5	1	16	2.02	9	0.44	39.5	1.7	17.5
1202	6	22.5	-	-	2.31	13	0.44	39.5	-	-
1856	6	22.5	-	-	2.56	18	0.72	4	-	-
1757	11	16	2	14	3.30	34	0.67	12.5	-	-
4515	-	-	-	-	2.93	28	0.65	15	0.2	20
2801	2	34.5	-	-	2.46	15	0.54	26.5	-	-
2105	16	9	-	-	1.71	4	0.37	42	4.4	10
5111	15	10	-	-	2.26	11	0.42	41	2.8	13
0106	9	18	6	5.5	3.59	38	0.63	18	9.0	8
4707	5	27	-	-	0.90	2	0.19	43	2.5	15
3705	11	16	-	-	3.63	39	0.72	4	3.9	11
1314	17	8	4	10	2.53	17	0.47	37	1.7	17.5
1246	3	31.5	-	-	3.07	31	0.61	21	-	-
4512	22	5	7	3	3.56	37	0.67	12.5	2.6	14
3415	1	38	-	-	2.79	24	0.55	24	-	-
4724	6	22.5	-	-	3.44	36	0.69	6.5	0.1	26.5
1229	12	13.5	-	-	2.64	19.5	0.49	36	-	-
4507	14	11	-	-	3.65	40	0.66	14	3.5	12
1303	6	22.5	-	-	2.68	22	0.50	34.5	0.1	26.5
2403	3	31.5	-	-	2.19	10	0.46	38	2.2	16
3423	1	38	-	-	2.48	16	0.51	31.5	-	-
1843	3	31.5	-	-	3.25	33	0.68	9.5	0.1	26.5
2102	1	38	-	-	2.28	12	0.56	23	0.1	26.5
4229	-	-	-	-	1.90	7	0.50	34.5	0.1	26.5
0107	3	31.5	-	-	3.68	41	0.72	4	0.1	26.5
5105	-	-	-	-	1.80	6	0.54	26.5	0.1	26.5
2402	1	38	-	-	2.89	26	0.63	18	0.2	20
5403	4	29	-	-	1.76	5	0.68	9.5	0.1	26.5
4222	1	38	-	-	2.86	25	0.69	6.5	0.2	20
5404	-	-	-	-	1.92	8	0.74	2	0.1	26.5
N	40		16		44		44		31	

APPENDIX A4. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: NUMBER OF PHYTOPLANKTON SPECIES, NUMBER OF PHYTOPLANKTON SPECIES (MODIFIED), PHYTOPLANKTON CONCENTRATION, AND PHYTOPLANKTON BIOVOLUME

STORET NUMBER	NUMBER OF PHYTOPLANKTON SPECIES (taxa/sample)	RANK	NUMBER OF PHYTOPLANKTON SPECIES (MODIFIED) (taxa/sample)	RANK	PHYTOPLANKTON CONCENTRATION (algal units/ml)	RANK	PHYTOPLANKTON BIOVOLUME ($\mu^3 \times 10^6$/ml)	RANK
1209	54	4	32	1	150,737	3	1202.73	3
1227	17	37.5	10	31	27,313	13	381.40	5
1752	46	8	26	3.5	12,298	18	71.00	9
1758	26	28	10	31	31,927	12	13.62	15
1849	55	2.5	26	3.5	154,639	2	65.15	10
1217	29	25	14	21.5	166,883	1	346.46	6
1201	43	9.5	20	9.5	41,553	8	392.81	4
1755	40	14.5	12	25	6,212	23	179.48	7
1740	25	29.5	10	31	1,980	35	0.90	40
1766	55	2.5	21	6	127,447	4	86.67	8
1002	10	41.5	6	38	4,352	26	1496.15	1
3917	56	1	31	2	38,280	9	19.54	13
1712	40	14.5	24	5	110,262	5	29.99	12
3412	20	35	4	42	234	42	0.32	43
1708	24	32	10	31	4,852	25	2.84	33
1202	38	17	20	9.5	105,280	6	1376.81	2
1856	12	40	4	42	397	41	5.19	25
1757	31	23	20	9.5	9,857	20	9.15	20
4515	23	34	9	34	183	44	0.54	42
2801	24	32	8	36	1,214	37	1.53	36
2105	25	29.5	11	27.5	14,544	15	2.62	34
5111	42	11.5	13	23	7,165	22	5.73	23
0106	53	5	20	9.5	12,736	17	4.36	28
4707	47	6.5	12	25	32,610	11	1.51	37
3705	33	20.5	16	17.5	2,103	30	3.55	30.5
1314	42	11.5	15	19.5	24,946	14	3.55	30.5
1246	33	20.5	16	17.5	48,308	7	59.39	11
4512	39	16	17	15.5	13,603	16	9.77	19
3415	34	19	10	31	3,723	27	6.52	22
4724	32	22	17	15.5	2,025	33	1.05	39
1229	43	9.5	19	13.5	33,784	10	18.88	14
4507	47	6.5	14	21.5	11,228	19	10.79	18
1303	41	13	20	9.5	8,053	21	6.66	21
2403	28	26.5	5	39.5	3,431	28	3.47	32
3423	30	24	8	26	2,082	31	5.35	24
1843	28	26.5	15	19.5	1,055	38	5.02	26
2102	17	37.5	12	25	1,290	36	3.76	29
4229	14	39	5	39.5	1,983	34	1.38	38
0107	35	18	20	9.5	5,226	24	2.51	35
5105	10	41.5	19	13.5	2,067	32	11.15	16
2402	24	32	11	27.5	2,481	29	4.58	27
5403	6	43.5	4	42	735	40	0.71	41
4222	18	36	8	36	966	39	10.90	17
5404	6	43.5	2	44	208	43	0.16	44
N	44		44		44		44	

APPENDIX A5. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: NYGAARD'S MYXOPHYCEAN, CHLOROCOCCALEAN, EUGLENOPHYCEAN, DIATOM, AND COMPOUND

STORET NUMBER	NYGAARD'S MYXOPHYCEAN INDEX	RANK	NYGAARD'S CHLOROCOCCALEAN INDEX	RANK	NYGAARD'S EUGLENOPHYCEAN INDEX	RANK	NYGAARD'S DIATOM INDEX	RANK	NYGAARD'S COMPOUND INDEX	RANK
1209	6.50	4.5	15.50	1	0.07	21.5	2.00	3.5	24.50	3
1227	-	-	-	-	-	-	-	-	-	-
1752	6.00	7.5	12.00	4	0.44	7	0.62	25	31.00	2
1758	1.67	27.5	2.67	22	-	-	1.00	14	5.67	26
1849	9.00	1	15.00	2	0.46	6	0.50	28.5	38.00	1
1217	7.00	1.5	14.00	3	0.10	18	0.25	39	24.00	4
1201	-	-	-	-	0.06	23	3.00	2	-	-
1755	2.50	22.5	3.25	19.5	-	-	0.75	21.5	7.25	22
1740	5.00	11	2.00	23	0.86	3	2.00	3.5	17.00	9.5
1766	6.50	4.5	9.50	7	0.09	19.5	0.50	28.5	20.00	5.5
1002	-	-	-	-	-	-	-	-	-	-
3917	3.50	19	9.50	7	0.31	11	1.33	7.5	19.00	7
1712	4.50	13.5	5.50	11	0.15	13.5	1.67	5.5	14.00	12
3412	-	-	-	-	0.50	5	0.07	41	-	-
1708	-	-	-	-	1.00	2	0.80	20	-	-
1202	4.33	15.5	5.33	12	-	-	0.20	40	10.00	16.5
1856	5.00	11	1.00	28	-	-	1.00	14	7.00	23
1757	3.00	20.5	1.67	25	-	-	0.33	37.5	5.33	27
4515	0.67	31	0.33	32	0.33	9.5	0.75	21.5	3.33	29
2801	-	-	-	-	1.20	1	5.00	1	-	-
2105	-	-	-	-	0.80	4	0.50	28.5	-	-
5111	4.50	13.5	4.00	16	0.41	8	0.43	32.5	13.50	13
0106	4.00	17.5	9.50	7	0.04	24	0.67	23.5	17.00	9.5
4707	1.50	29	3.50	17	-	-	1.25	9	7.50	20.5
3705	7.00	1.5	9.00	9	-	-	1.33	7.5	20.00	5.5
1314	2.25	25	3.25	19.5	1.4	15	1.00	14	7.50	20.5
1246	2.33	24	0.50	30.5	-	-	0.40	34	3.17	31
4512	3.00	20.5	4.67	15	-	-	0.67	23.5	9.00	18
3415	1.67	27.5	3.33	18	0.07	21.5	1.00	14	6.33	25
4724	4.00	17.5	5.00	13.5	0.11	16.5	1.00	14	11.50	14
1229	4.33	15.5	6.33	10	0.03	25	0.50	28.5	11.30	15
4507	2.20	26	1.80	24	0.15	13.5	0.37	35	5.20	28
1303	-	-	-	-	0.17	12	0.36	36	-	-
2403	2.50	22.5	0.50	30.5	0.33	9.5	1.00	14	6.50	24
3423	5.00	11	10.00	5	-	-	1.00	14	18.00	8
1843	6.00	7.5	5.00	13.5	0.09	19.5	0.43	32.5	15.00	11
2102	-	-	-	-	-	-	1.00	14	-	-
4229	6.00	7.5	1.00	28	-	-	0.50	28.5	8.00	19
0107	0.80	30	1.20	26	-	-	0.86	19	3.20	30
5105	-	-	1.00	28	-	-	0.50	28.5	2.00	32
2402	-	-	-	-	0.11	16.5	1.67	5.5	-	-
5403	-	-	-	-	-	-	1.00	14	-	-
4222	6.00	7.5	3.00	21	-	-	0.33	37.5	10.00	16.5
5404	-	-	-	-	-	-	-	-	-	-
N	31		32		25		41		32	

APPENDIS A6. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: BOLAND $PC1_1$, BOLAND $PC1_2$, VOLLENWEIDER TROPHIC RATIO, DILLON TROPHIC RATIO, AND LARSEN-MERCIER TROPHIC RATIO

STORET NUMBER	BOLAND $PC1_1$	RANK	BOLAND $PC1_2$	RANK	VOLLEN-WEIDER TROPHIC RATIO	RANK	DILLON TROPHIC RATIO	RANK	LARSEN-MERCIER TROPHIC RATIO	RANK
1209	-	-	-	-	-	-	-	-	-	-
1227	4.83	1	4.27	2	75.62	1	-	-	259.90	1
1752	3.49	4	-	-	-	-	-	-	-	-
1758	4.67	2	4.36	1	29.42	2	74.00	1	61.77	3
1849	-	-	3.64	3	-	-	-	-	-	-
1217	3.91	3	3.56	5	-	-	-	-	79.90	2
1201	3.13	7	-	-	-	-	-	-	38.92	4
1755	2.76	8	-	-	12.66	5	3.40	12	10.81	10
1740	1.35	13	1.91	7	5.43	9	15.38	4	14.61	7
1766	3.40	5	3.63	4	1.96	21	12.00	5	11.81	8
1002	2.50	9	1.84	8	9.25	6	5.67	10	5.58	14
3917	3.35	6	3.02	6	5.02	11	18.67	3	18.57	6
1712	1.73	11	-	-	7.42	7	7.33	8	7.40	12
3412	-1.12	16	0.23	10	18.92	3	3.33	13	3.17	16
1708	1.17	14	1.71	9	15.91	4	7.50	7	8.57	11
1202	2.37	10	-	-	3.94	13	22.00	2	19.17	5
1856	1.48	12	-	-	4.54	12	5.92	9	5.80	13
1757	-	-	-	-	-	-	-	-	-	-
4515	-	-	-1.45	22	5.07	10	11.39	6	1.84	24
2801	-	-	-	-	2.58	17	1.88	19	11.28	9
2105	-	-	0.09	13	2.10	19	2.32	17	2.35	18
5111	-	-	-0.02	14	2.24	18	2.21	18	2.20	21
0106	-	-	0.19	11	5.72	8	4.20	11	4.84	15
4707	-	-	0.10	12	3.61	14	2.43	16	2.28	19
3705	-	-	-0.65	17	3.13	16	1.74	20	2.04	23
1314	-	-	-0.43	15	3.44	15	3.25	14	3.12	17
1246	-0.73	15	-	-	-	-	-	-	-	-
4512	-	-	-0.51	16	1.70	23	1.55	22	1.51	26
3415	-1.87	18	-0.94	18	0.34	34.5	1.00	26	1.32	27
4724	-	-	-1.45	23	1.11	27	2.70	15	2.22	20
1220	-1.23	17	-	-	-	-	-	-	2.11	22
4507	-	-	-0.98	19	1.49	24	1.56	21	1.52	25
1303	-	-	-2.40	30	0.56	29	1.10	25	1.06	31
2403	-	-	-1.10	20	0.18	36	0.76	31	0.71	35
3423	-	-	-	-	0.48	32	0.96	27.5	1.13	29
1843	-2.36	19	-1.25	21	0.75	28	1.33	23	1.20	28
2102	-	-	-2.45	31	0.49	33	0.47	34	0.49	38
4229	-2.54	20	-2.18	28	0.50	31	1.12	24	1.10	30
0107	-	-	-1.98	25	1.35	25	0.96	27.5	1.04	32
5105	-	-	-1.46	24	1.72	22	0.69	32	0.66	36
2402	-	-	-2.16	27	0.34	34.5	0.38	35	0.39	39
5403	-	-	-2.24	29	1.28	26	0.83	30	0.83	34
4222	-	-	-2.14	26	0.54	30	0.59	33	0.55	37
5404	-	-	-2.75	32	2.02	20	0.04	29	0.95	33
N	20		32		36		35		39	

APPENDIX A7. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: TOTALP(PD), CHLA(PD), KJEL(PD), TOTALP/CONC(P), AND CHLA/CONC(P)

STORET NUMBER	TOTALP(PD)	RANK	CHLA(PD)	RANK	KJEL(PD)	RANK	TOTALP/CONC(P)	RANK	CHLA/CONC(P)	RANK
1209	268	1	45.0	4	1440	6	12251	2	1470	3
1227	250	2	49.0	2	1642	3	1371	13	303	13
1752	223	3	30.5	12.5	1215	11.5	3894	6	164	19
1758	147	14	37.6	7	1437	7	1802	11	490	8
1849	190	5	43.0	5	1486	5	17332	1	1072	4
1217	204	4	46.0	3	1648	2	5210	4	1008	5
1201	174	6	38.0	6	1342	9	3399	7	462	9
1755	136	17.5	30.9	11	1108	22	332	26	100	22
1740	159	8	29.0	16	1136	18	198	29	21	34.5
1766	116	23	35.0	8	1215	11.5	5042	5	667	7
1002	160	7	75.0	1	1706	1	393	23	1751	2
3917	154	9.5	25.8	19	931	28	3073	8	442	10
1712	152	12.5	32.0	9.5	1199	13.5	5353	3	704	6
3412	97	30.5	18.0	35	963	25	190	30	9	41
1708	134	20	23.0	25.5	878	30.5	524	19	71	23
1202	99	29	29.5	15	1488	4	1430	12	430	11
1856	109	24	22.0	28.5	946	27	44	43	8	42
1757	75	41	25.0	20	1358	8	817	16	12160	1
4515	82	8	9.0	43	571	43	85	39	2	43
2801	96	32	12.0	41	821	33	115	36	32	31
2105	103	27	30.0	14	1281	10	324	27	63	24
5111	94	34	18.1	34	774	37	369	24	188	16.5
0106	139	16	19.0	31	895	29	642	17	245	14
4707	106	26	30.5	12.5	1073	20	569	18	131	21
3705	136	17.5	23.0	25.5	973	24	349	25	34	29
1314	142	15	28.0	17.5	1057	21	830	15	161	20
1246	91	36	24.0	22.5	1143	17	980	14	217	15
4512	97	30.5	24.0	22.5	1131	19	466	20	310	12
3415	76	40	13.3	40	682	39	186	31	33	30
4724	63	43	10.4	42	622	42	120	35	17	36
1229	152	12.5	32.0	9.5	1199	13.5	2581	9	188	16.5
4507	154	9.5	22.0	28.5	958	26	1816	10	185	18
1303	95	33	28.0	17.5	1191	15	149	33	31.4	32
2403	80	39	18.2	33	805	35	107	37.5	44	27
3423	100	28	17.0	36.5	789	36	423	21	55	25
1843	134	20	23.0	25.5	878	30.5	73	40	13	38
2102	10	44	5.4	44	364	44	124	34	10.1	40
4229	74	42	18.6	32	842	32	47	42	10.4	39
0107	153	11	24.7	21	1181	16	290	28	49	26
5105	107	25	20.0	30	819	34	107	37.5	21	34.5
2402	86	37	17.0	36.5	679	41	151	32	36	28
5403	118	22	16.0	38.5	762	38	56	41	15	37
4222	134	20	23.0	25.5	995	23	404	22	25	33
5404	92	35	16.0	38.5	681	40	10	44	2	44
N	44		44		44		44		44	

APPENDIX A8. TEST LAKES WITH TROPHIC INDEX VALUES AND RANKS FOR THE FOLLOWING INDICES: KJEL/CONC(P), TOTALP/CONC(PD), CHLA/CONC(PD), KJEL/CONC(PD), AND MULTIVARIATE ALGAL INDEX(PD)

STORET NUMBER	KJEL/CONC (P)	RANK	TOTALP/CONC (PD)	RANK	CHLA/CONC (PD)	RANK	KJEL/CONC (PD)	RANK	MULTIVARIATE ALGAL INDEX (PD)	RANK
1209	62081	1	4744	2	797	1	26080	2	5.56	2
1227	11662	12	1133	9	266	6	10024	6	5.64	1
1752	12564	11	849	11	86	18.5	4182	13	5.36	6
1758	17565	8	1644	8	425	4	16153	4	5.18	8
1849	55885	2	7438	1	476	3	16931	3	5.54	3
1217	39083	3	2671	5	771	2	27947	1	5.45	5
1201	19671	6	683	12	148	14	5074	12	5.24	7
1755	2903	24	232	20	83	20	2082	20	4.98	13.5
1740	1104	34	133	27	11	35.5	433	37	5.00	12
1766	25994	4	2917	4	258	7	9027	7	5.08	11
1002	3917	19	353	18	169	11	3803	15	5.52	4
3917	17578	7	1964	6	281	5	11328	5	4.79	20
1712	22189	5	3386	3	210	8	7882	9	5.16	9.5
3412	1258	33	185	23	9	38	1227	24	4.29	36
1708	3104	23	410	15	62	22	2263	18	4.69	24.5
1202	16379	9	656	13	164	12	9022	8	4.98	13.5
1856	389	42	21	42	6	41	187	42	4.52	29
1757	5933	15	57	36	19	29.5	1049	27	4.68	26
4515	572	40	79	31	2	43	531	34	3.80	40
2801	943	39	60	35	26	26.5	528	35	4.44	31
2105	3150	21	112	29	33	25	1173	25	4.93	17
5111	2688	26	153	24	158	13	1299	23	4.49	30
0106	4377	18	203	21	192	9	1763	21	4.67	27.5
4707	4842	16	286	19	86	18.5	2856	16	4.88	18
3705	2179	28	111	30	18	31	521	36	4.72	22
1314	4489	17	366	17	64	21	2340	17	4.97	15
1246	10497	13	615	14	145	15	6745	10	4.70	23
4512	3785	20	188	22	171	10	1744	22	4.74	21
3415	1631	29	140	26	21	28	1108	26	3.76	41
4724	1099	35	74	32	13	34	811	31	3.50	43
1229	9610	14	1733	7	104	17	3913	14	5.16	9.5
4507	13319	10	996	10	108	16	6073	11	4.81	19
1303	1431	30	39	40	11	35.5	534	33	4.40	32.5
2403	1051	37	69	33.5	39	24	761	32	4.35	34
3423	2810	25	369	16	49	23	2215	19	4.31	35
1843	1030	38	52	38	9	38	298	40	4.69	24.5
2102	1057	36	4	44	2	43	139	43	2.32	44
4229	505	41	30	41	7	40	353	39	3.92	39
0107	2264	27	152	25	19	29.5	898	30	4.95	16
5105	1369	32	69	33.5	17	32	983	29	4.19	37
2402	1382	31	115	28	26	26.5	1019	28	3.72	42
5403	345	43	49	39	14	33	292	41	4.40	32.5
4222	3144	22	55	37	9	38	398	38	4.67	27.5
5404	132	44	10	43	2	43	132	44	3.97	38
N	44		44		44		44		44	

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